SERI

Solar Energy Research Institute
A Division of Midwest Research Institute

1617 Cole Boulevard
Golden, Colorado 80401

Operated for the
U.S. Department of Energy
under Contract No. DE-AC02-83CH10093

Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price:
Microfiche A01
Printed Copy A04

SERI/TR-253-2120
UC Category: 59
DE84004521

A Summary and Assessment of Historical Reliability and Maintainability Data for Active Solar Hot Water and Space Conditioning Systems

Gary J. Jorgensen

May 1984

Prepared under Task No. 1598.31
FTP No. 441-84

Solar Energy Research Institute
A Division of Midwest Research Institute

1617 Cole Boulevard
Golden, Colorado 80401

Prepared for the
U.S. Department of Energy
Contract No. DE-AC02-83CH10093

FOREWORD

This report documents the findings of a number of studies that directly address reliability and maintainability (R&M) issues involved with active solar energy systems. The intent is to consolidate these findings in a manner that will allow meaningful conclusions to be made about the present state of R&M concerns. Recommendations on future R&M needs and directions are formulated from conclusions based on the aggregated data. Support for this work was provided by the Active Heating and Cooling Program of the U.S. Department of Energy.

Charles F. Kutscher, Task Leader
Systems Effectiveness Research Program

Approved for

SOLAR ENERGY RESEARCH INSTITUTE

John P. Thornton, Chief
Thermal Systems and Engineering Branch

L. J. Shannon, Director
Solar Heat Research Division

ACKNOWLEDGMENTS

This report was prepared for the U.S. Department of Energy under SERI's Systems Effectiveness Research (SER) program for the Active Heating and Cooling Program. A portion of the "Collector Subsystem" section was contributed by Belinda Collins, Lawrence Salomone, and Karen Lister of the National Bureau of Standards. Chuck Kutscher, technical manager of the SER program at SERI, provided guidance and direction, useful background information and discussions, and reviewed the draft versions of this document.

Appreciation is extended to the following SERI reviewers: R. B. Farrington, W. Short, C. Bircher, A. A. Lewandowski, L. M. Murphy, C. Christensen, R. Judkoff, and D. Wortman. Additional thanks are extended to the following external reviewers: R. D. Dikkers, National Bureau of Standards, P. J. Pekrul, Rockwell International, W. M. Jones, ESG Inc.; R. Spears, Reynolds Products and Process Development Laboratory; S. Moore, Los Alamos National Laboratory, G. Purcell, Electric Power Research Institute, J. W. Mitchell, University of Wisconsin; and P. Thompson, Ohio State University.

SUMMARY

Objective

To consolidate relevant reliability and maintainability (R&M) information based on documented findings from field installations.

Discussion

Twenty applicable R&M studies are identified and summarized. Whenever possible, analogous data from the various studies are compared and combined to give a clearer, more complete representation of pertinent R&M issues. Data from government-sponsored demonstration projects, utilities, private consultants, and owner surveys are included. Failure rates and problem frequencies are emphasized rather than guidelines and experiences that have been compiled elsewhere. R&M issues concerning solar energy systems, subsystems, and components are reviewed.

The majority of R&M data discussed deals with liquid systems for solar domestic hot water applications. Drainback and recirculation systems were found to be the most reliable of the liquid systems; antifreeze and oil systems were moderately reliable. Draindown systems and systems using electric resistance heating to prevent freezing were the least reliable of the liquid systems studied.

Conclusions

At the subsystem level, storage was found to be the most reliable of those subsystems considered. Storage problems are generally not severe, and their impact on system operation is minimal. Problems that occur are usually traceable to improper installation or maintenance. Transport subsystems experience a relatively large number of problem incidences, but these also are generally not severe. Strong evidence exists that many transport problems can be eliminated by improved design and installation practices and proper maintenance. Collector subsystems exhibit low reliability with 30%-50% of the surveyed systems reporting some type of collector problem. Failures attributed to leaks, damaged glazing seals and gaskets, and freezing are the most prevalent collector problems and need to be further addressed. Control subsystems experience fairly high incidences of problems, although the level of severity tends to be low. Temperature sensor quality, placement, and installation are more critical than inherent faults with the controller hardware component.

Overall, storage units and heat exchangers are the most reliable solar components, although piping/ducts, controls, and collectors exhibit relatively poor reliability and require further R&M research. Pumps, fans, valves, and dampers are intermediately reliable.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

ANL	Argonne National Laboratory
CPVC	chlorinated polyvinyl chloride
DHW	domestic hot water
DOE	Department of Energy
ESG	Energy Systems Group
HUD	Housing and Urban Development
HVAC	heating, ventilation, and air conditioning
LILCO	Long Island Lighting Company
MTBF	mean time between failures
NBS	National Bureau of Standards
NEES	New England Electric System
NESEC	Northeast Solar Energy Center
NSDN	National Solar Data Network
NSDP	National Solar Demonstration Program
PNM	Public Service Company of New Mexico
R&M	reliability and maintainability
SC	space cooling
SDHW	solar domestic hot water
SEP	Site Evaluation Program
SER	Systems Effectiveness Research
SERI	Solar Energy Research Institute
SH	space heating
TVA	Tennessee Valley Authority
UV	ultraviolet

SERI

SECTION 1.0

INTRODUCTION

1.1 BACKGROUND

As a result of the Arab oil embargo in 1973, the U.S. government began to focus attention on the use of solar energy to displace fossil fuel. A number of government-sponsored programs were instituted specifically aimed at demonstrating the feasibility of using solar heating and cooling in residential and commercial buildings. Public interest in solar energy and solar-related tax incentives gave rise to a dramatic increase in the number of private companies engaged in solar system manufacture, marketing, and installation. A number of public utilities across the country also initiated residential solar energy programs [1]. The result of this activity was an increase in the number of homes featuring active solar systems in the United States from less than 5000 in 1974 to over 160,000 in 1980 [2].

Since the economics of solar systems depend directly upon the performance of such systems, a number of efforts were made to monitor the operation of selected installations. The level of instrumentation used in these undertakings ranged from Btu-meters to determine energy output [3] to an array of temperature, flowrate, and radiation sensors [4] to yield subsystem efficiencies. In general, the results were discouraging. System efficiencies were often much lower than expected. Major failures were common.

Since many problems were traceable to improper design and installation, a number of design handbooks were prepared, and workshops for designers and installers were held. By the end of the 1970s it became apparent that failures were still prevalent; system efficiency information and operational performance were not sufficient to quantify the cause and frequency of solar system failures.

Although some attempts were made to gather reliability and maintainability (R&M) data, this was often done as a secondary effort in a performance study. No broad-based program to acquire R&M data equivalent to the Department of Energy (DOE) and Department of Housing and Urban Development (HUD) attempts in performance monitoring was ever established. As a result, R&M data on solar systems are of varying quality and is scattered throughout the literature.

It is the purpose of this report to consolidate the findings of previous R&M studies into a single document and thereby draw conclusions regarding R&M issues based on the combined data. The emphasis was placed on hard reliability data (e.g., failure rates) as opposed to design guidelines and informal field experiences, which have been related elsewhere [5-13].

The important characteristics of the information used for this study are summarized and presented in Table 1-1. Each data source has been assigned a study number that will be used throughout this report. Each study listed in Table 1-1 is identified by the organization performing the work and that organization's classification (national laboratory, utility company, etc.), and applicable references to the literature are given. The number and types

Table 1-1. R&M Data Studies

Study No.	Organization	Type of Organization	Number of Systems	Type of Systems	Region of Study	Dates of Installation	Dates of Study	Purpose of Study	Type of Study[a]	Relevancy of Data[b]	Notes/Remarks	References
1	National Bureau of Standards (NBS)	Natl. Lab	110	—	Throughout USA	--[c]	9/75-12/79	National Residential Solar Demonstration Program	R	2	Cycle I	14
2	NBS	"	246	50% New; 50% Retrofit	"	—	10/76-5/80	"	R	2	Cycle II; highest No. of instrumented sites of 4 Cycles	14
3	NBS	"	355	—	"	—	5/77-6/80	"	R	2	Cycle III	14
4	NBS	"	212	—	"	—	3/78-11/79	"	R	2	Cycle IV	14
5	NBS	"	25	—	"	—	—	National Commercial Solar Demonstration Program	R	2	Pon I	14
6	NBS	"	41	—	"	—	—	"	R	2	Pon II	14
7	NBS	"	24	Large-scale, hot water systems	"	—	—	"	R	2	Hotel/Motel	14
8	Argonne National Laboratory (ANL)	"	47	Water (16) Glycol (19) Oil (1) Air-space heat (2) Air-space heat and DHW (9)	"	—	—	Evaluate freezing problems	R	3	—	15,16
9	ANL	"	40,66	—	"	—	1976-6/78 (40) 7/78-4/79 (66)	Improvements in R&M	R	2	National Solar Demonstration Program sites; collector controls, freezing, and interconnection problems found	17-19
10	ANL	"	80	Water (61) Air (8) Tracking (7) Tubular (4)	"	—		National Commercial Solar Demonstration Program	R	1	—	20
11	Solar Environmental Engineering Co. and Solar Control Corp.	Subcontracter for SERI	12	Space heat & DHW (8): Glycol (2) Air (6) DHW only (4): Glycol (2) Air (1) Water (1)	Colorado	—	11/78-2/79	Controller performance	I,S	1	Mechanical inspection of HUD sites	21,22
12	Vitro Labs	Subcontracter for SERI	16	DHW (6) Space heat and DHW (8) Space heat (1) Space cool (1)	Throughout USA	—	10/81-9/82	Provide quantitative data on R&M of solar heating and cooling system components	M,R	3	NSDN sites	23
13	Northeast Solar Energy Center (NESEC)	Regional Center	170	DHW; Antifreeze (156) Drainback (11) Draindown (2) Phase change (1)	New England New York New Jersey Pennsylvania	—	11/80-2/81	To investigate the state of the art of installation techniques and system durability in the field.	I	2	Residential systems	24
14	Energy Systems Group (ESG)	"	136	DHW; Recirculating (63) Antifreeze (29) Drainback (22) Draindown (13) Manual (5) Thermosiphon (2)	Southeast USA: Florida (85) Virginia (14) Alabama (12) Georgia (4) S. Carolina (4) N. Carolina (8) Texas (7) Kentucky (2)	—	7/81-5/82	Generate operational reliability to identify problem areas for further R&D	M,S,W	2	—	25,26

Table 1-1. R&M Data Studies (Concluded)

Study No.	Organization	Type of Organization	Number of Systems	Type of Systems	Region of Study	Dates of Installation	Dates of Study	Purpose of Study	Type of Study[a]	Relevancy of Data[b]	Notes/Remarks	References
15	New England Electric System (NEES)	Utility	100	DHW; Drainback (2) Draindown (24) Antifreeze (48) Air (4) Freezable (22)	New England	11/75-5/76 (30) 7/76-11/76 (70)	First year of operation	To shed winter energy peak heating loads	I,R	1	Lessons-learned format	27
16	Public Service Company of New Mexico	"	29	DHW; Oil (6) Draindown (2) Drainback (1) Air (2) Glycol (18)	New Mexico	5/78-5/79 (10) 8/79-7/80 (19)	5/78-7/80	To determine average system performance, economics, and load characteristics	W	2	--	28,29
17	Long Island Lighting Co. (LILCO)	"	632	DHW; Drainback	Long Island, N.Y.	10/78-10/80	10/78-12/80 +1982	To determine equipment performance and service requirements	W	3	Identical systems	30-32
18	Tennessee Valley Authority (TVA)	"	1000	DHW; Glycol	Memphis, Tenn.	2/79-5/81	2/79-6/82	Load management	W	3	Two collector types; otherwise identical systems	33,34
19	University of Maryland	University	177	DHW (40) Space heat (53) Space heat and DHW (78)	New England (88) and southwest USA (89)	1973-1978 (72% since 1976)	1973-1978	--	S	1	Owner assessment (survey)	35
20	Northern Energy Corp.	Private study	124	DHW	Northeast USA	1978-1980	1978-1980	To determine how well SDHW systems work and what problems occur	S	1	HUD approved SDHW	36

[a]I = Site Inspections
M = Instrument Monitored
R = Operational Reports Data Base
S = Survey
W = Warranty Claim Information

[b]1 = Very useful R&M data
2 = Moderately useful R&M data
3 = Some useful R&M data

[c]Not applicable or data not available.

of systems involved and the geographic locale distinguishing each study are reported. In general, region and system type will exhibit some correlation; systems in nonfreezing climates (for example, Florida) tend to be recirculation or drainback/draindown water systems, whereas those in colder areas (for example, New England) emphasize an antifreeze approach.

Because the state of the art of solar energy system design and manufacturing has expanded rapidly in the last ten years and because R&M problems have been widely publicized in published guidelines [5-7], handbooks, experiences [8] and articles detailing lessons learned [9-13] with earlier systems, the time period of a given study is important. Further, to avoid biasing results by infant mortality rates of failed components [18], the time window of a given study relative to system installation and start-up is critical. These data are also indicated in Table 1-1.

Finally, the quality and applicability of data to R&M concerns are related to the ultimate goal of a given project at its inception. If the interest was to monitor system performance and R&M was only a secondary concern, then it is likely that any such data gathered or generated will only be of secondary relevance and quality. Unfortunately, few studies have exhibited R&M planning. A recent survey [26] found that

> "...there are at least 18 organizations throughout the country conducting some type of monitoring program to analyze the thermal performance of solar hot water systems. However, little information is available on the reliability of different solar system types along with the different types of problems encountered."

A description of the purpose of each study, applicable notes and remarks, an indication as to the type of study (monitored sites, on-site inspections, owner survey, etc.), and a subjective classification of the R&M relevancy of the data included in each study are also included in Table 1-1. Whenever data are not applicable or not available in this and all other tables in this report, a double dash notation (--) is used.

1.2 REVIEW OF DATA SOURCES

The objective of this effort was to consolidate all relevant reliability and maintainability information based on documented findings from field installations. Failure rates and problem frequencies are emphasized rather than guidelines and experiences, which have been compiled elsewhere. Research efforts are not discussed in detail, but references to applicable work are given.

Wherever possible, analogous data from different studies are compared and combined to give a clearer, more complete representation of pertinent R&M issues. This process has been difficult because of the diverse way in which R&M information has been gathered, analyzed, and reported. As indicated in Table 1-1, a large variation exists between studies in such areas as purpose and emphasis, data gathering techniques, geographic location, and time period. In addition, the studies often differ in how problems are defined (in terms of severity and complexity), and how the data are grouped and presented (raw vs.

analyzed data, etc.). A summary and a discussion of the unique aspects of each study listed in Table 1-1 follows.

The National Bureau of Standards studies summarizing the National Solar Heating and Cooling Demonstration Program point out that the data analyzed "were never intended to be used exclusively for a reliability program and were reported in a different context" [14]. Failure data for the residential programs (studies 1-4) came from a computerized data file of "Technical Concerns"; commercial failure data (studies 5-7) were derived from monthly management reports. Problems exhibited prior to system acceptance or completion were not reported.

These studies analyze the reported problems as a function of time from system installation. Each problem is rated according to the severity of its impact upon system operation (complete shutdown vs. partial shutdown vs. no effect). For each study, cumulative system failures are displayed as a function of time for the overall system and for four subsystems; namely, collector, transport, storage, and controls.

Studies 8-10 are based upon subsets of data from the National Commercial Solar Demonstration Program available at the time of each study. These studies were performed by Argonne National Laboratory under the auspices of their Solar Data Project Program [37]. Although expressly charged with obtaining and evaluating R&M data from the solar demonstration sites, as mentioned above, the demonstration program was not specifically geared to easily provide such data. The objectives of the program involved obtaining R&M data on solar energy systems from the operational solar demonstration sites and identifying problems that degraded system performance or caused system failures. Data were basically gathered from monthly progress reports issued by the various agencies overseeing the operation of the commercial demonstration sites.

For each of the ANL studies (8-10), failures are reported as the fractional number of problem incidences experienced by a particular type of system (for example, water vs. antifreeze vs. air). Types of problems include instances of leaks or freezing and problems with collectors or controls. Study 10 provides problem incidences and rankings of component failures for 80 solar systems. By comparing failure rates over equivalent time periods from year to year these studies are thus able to indicate trends in the reliability of various types of systems as a function of time and failure mode.

Study 11 consists of mechanical inspections by a reliability assessment team of twelve systems in Colorado during the winter of 1978-79. The dozen systems had all been in operation for roughly one year. Problem incidences are reported as a function of component type vs. cause of failure (component, design, installation, or operation/maintenance). Although the emphasis is on controller performance, useful R&M data on a wide variety of components are given.

The purpose of study 12 was to obtain quantitative R&M data from 16 instrumented sites included in the National Solar Data Network (NSDN). Data were gathered for a one year period. Collection of data was automated for pumps and fans, failures of other components considered (piping, controllers, heat exchangers, and automatic valves) were provided by nonautomated means. Estimates of reliability are based upon catastrophic failures; intermittent, repairable, or degradation failures are not considered.

Study 13 entails site inspections of 170 systems in the northeastern United States. Six teams of qualified personnel comprised a Site Evaluation Program (SEP) for the Northeast Solar Energy Center (NESEC). They visited systems that had been in service for 1-2 years during the winter of 1980-81. Many recurrent problems, primarily traceable to poor installation practices, were uncovered. Many of the results of this study are phrased in terms of tips or guidelines. The frequency with which particular R&M problems occur are given for a number of components.

R&M data for a variety of systems in the southeast United States are reported by the Energy Systems Group under contract to DOE in study 14. This work was conceived and begun under the auspices of the Southern Regional Solar Energy Center. Eighty-six sites in Florida averaging 11.4 months of monitoring and 51 sites in the Southeast exclusive of Florida averaging 7.4 months of monitoring were studied between July 1981 and May 1982. Operational down-times are given as a function of system type and component failure. In addition, the types of problems experienced by each system are reported. Control and leakage problems were found to be the most prevalent.

A trouble analysis by system type vs. failure mode is presented in study 15. One-hundred systems installed in single-family residences owned by customers of the New England Electric System (NEES) were surveyed during their first year of operation. Although much of this study has a lessons-learned flavor, good R&M data are given in the trouble analysis. Also, the time frame (~1976) provides a useful glimpse of the state of R&M of various solar systems early in the government's involvement with these issues.

The Public Service Company of New Mexico (PNM) conducted a two-phase solar domestic hot water (SDHW) demonstration program between January 1978 and December 1982. Although the primary objectives of the program were to determine system performance, economics, and load characteristics, service problems were available from manufacturer warranty invoices. During Phase I, ten systems were chosen and purchased by PNM between May 1978 and May 1981. Nineteen owner-selected SDHW systems were installed between August 1979 and July 1980 during Phase II with some early operational results available from Phase I to guide selection. An installation and operational problem matrix is given for all systems included in study 16. No improvements were found in installation techniques or component reliability between the two phases of the project.

Study 17 concerns an SDHW demonstration program undertaken by the Long Island Lighting Company (LILCO) in 1978. By June 1980 632 systems were installed; R&M data are available through December 1982. The LILCO system is a two-collector, 120-gal, stone-lined storage tank drainback configuration with an internal heat exchanger. The system was selected by LILCO from roughly 150 considered; systems were sold by LILCO and installed and serviced by contractors trained by the utility and the manufacturer. Five-year warranties were issued for these systems, which provide the basis for documenting R&M problems. Many problems were experienced with these systems early during their service lifetimes. In particular, problems with the controller, the storage tank, and the tempering valve were common.

Study 18, the Memphis 1000 SDHW demonstration project, was initiated by the Tennessee Valley Authority (TVA) in August 1978. The system was designed by TVA, which also was involved with system installation and inspection. One-thousand glycol systems were installed between February 1979 and May 1980. Half of the systems employed collectors with selective surfaces; half had non-selective surfaces. An 82-gallon solar storage tank and a 120-gallon auxiliary tank were used. Based upon time of installation, some systems used a single pump and a tank-mounted internal heat exchanger; others employed two pumps and an external counterflow heat exchanger. Failure rates of the various system components are available from service summaries for the Memphis 1000 project.

Experiences of 177 nonsubsidized, decentralized solar energy consumers are surveyed in study 19. The data gathered were analyzed according to manufacturer of the system (packaged vs. contractor-made vs. homemade) rather than by function type (DHW vs. space heating vs. combined) or by geographic locale (New England vs. southwest United States). The frequency of technical malfunctions are presented as a function of problem area. Over 50% of the systems considered experienced problems in the first three months of operation; over 40% experienced problems thereafter.

The maintenance requirements of 124 HUD-approved SDHW systems installed in the northeastern United States between 1978 and 1980 are presented in study 20. Good R&M data are given, although this project was primarily intended as a performance monitoring task. Maintenance information was supplied by the homeowners (who had 5-year system warranties). Each maintenance occurrence is tabulated by type (component problem) and by origin (installer, manufacturer, other, or unknown). This study indicates that 48% of the sites included required no solar-related maintenance. Further, excluding control system failures and collector fogging, solar components exhibited roughly the same reliability as conventional back-up systems.

SECTION 2.0

COMPARISON OF RELIABILITY OF SOLAR ENERGY SYSTEMS

As is evident in the "Type of System" column in Table 1-1, very little quantitative data comparing reliability issues of domestic hot water (DHW) vs. space heating (SH) vs. space cooling (SC) systems were found in the literature. The vast majority of the studies included in this report deal with DHW systems only. Studies that contrast various types of systems (for example, study 11) contained small data bases (i.e., a small number of systems), making significant conclusions difficult. Other studies that included a large number of comparable systems (for example, studies 1-7) treat R&M problem incidences on an aggregate basis and do not report separate DHW/SH/SC statistics. Thus, after a brief comparison of the main functional solar systems, this section concentrates on the various types of SDHW systems.

The emphasis of study 11 is on solar controller reliability. Inspection of over a hundred solar installations revealed that nearly 80% of the system owners were satisfied with the performance of DHW controllers. Less than 20% of those surveyed indicated satisfaction with the SH and SC control units. Detailed information on the overall problem incidences of a dozen systems is presented and is summarized in Table 2-1. The average number of reported problems per type of system was found to be 6.8 for the SH + DHW systems compared to 4.0 for the DHW-only systems. Moreover, each category of DHW-only system (air, glycol, water) had fewer problems per system than the analogous SH + DHW units. Based on the small sample size (12 total ystems), study 11 indicates that DHW-only systems are relatively more reliable than combined SH + DHW systems. This result is not unexpected because of the increased complexity of SH + DHW systems compared to the DHW-only systems.

Study 8 indicates that combined SH + DHW systems are less reliable than SH-only systems as well. Again, for a small number of total systems (11), study 8 reports that three instances of freezing occurred out of nine SH + DHW systems, whereas neither of the two SH-only systems experienced any freeze-related problems.

The problem incidences associated with the HUD residential National Solar Demonstration Program (NSDP) (studies 1-4) were further analyzed by Freeborne and Mara [38] on the basis of liquid vs. air systems for heating and hot water use. It was found (Table 2-2) that 73% of 289 liquid systems experienced problems, as opposed to only 48% of 280 air systems. Of the liquid systems that reported problems, an average of 3.3 problems per failed system were experienced; 2.9 problems per failed system were encountered by affected air systems.

Throughout this report a statistical test, known as the normal deviate test, is applied to determine the statistical significance between various percentages of problem incidences. As pointed out in Appendix A, this test is only strictly appropriate when a sufficiently large number (over 30) of systems is included within a particular comparison category. If all test conditions are uniform between one study and another study (for example, studies 1-7), then the results of these studies can be combined to obtain composite percentages

Table 2-1. Reliability Problems Reported by Study 11

	SH and DHW				DHW				Total			
	Air	Glycol	Water	Sub-total	Air	Glycol	Water	Sub-total	Air	Glycol	Water	Total
No. of systems	6	2	0	8	1	2	1	4	7	4	1	12
No. of problems reported	43	11	0	54	4	8	4	16	47	19	4	70
Average No. of problems/system	7.2	5.5	--	6.8	4.0	4.0	4.0	4.0	6.7	4.8	4.0	5.8

Table 2-2. Problem Incidences of Liquid vs. Air Systems for Single Family Heating and Hot Water Systems [38]

System Type	No. of Systems	No. of Systems with Problems	Percentage of Systems with Problems	Problem Incidences: Collector	Transport	Storage	Controls	Total
Liquid	289	212	73	214	173	150	157	694
Air	280	134	48	88	163	56	81	388
TOTAL	569	346	61	302	336	206	238	1082

(based on many aggregated systems) that can be compared by the normal deviate test. Unfortunately, the diverse manner in which data were gathered and analyzed in the majority of studies included in this report precludes this procedure. Indeed, the significance of aggregated percentages must be carefully considered. For example, consider the following hypothetical case: study A is performed with great care and a broad interpretation of what constitutes a problem is applied (all types of problems, trivial to catastrophic, are recorded); study B is carried out with less care and only major problems are tallied. study A finds that 120 of 300 systems of type I and 30 of 50 systems of type II experience problems. study B finds that 6 of 60 systems of type I and 70 of 350 of type II experience problems. Both studies conclude that system type I is more reliable than system type II (40% vs. 60% for study A and 10% vs. 20% for study B). However, based on the combined results, the exact opposite conclusion would be made, namely that system II (25%) is more reliable than system I (35%). Although this is an extreme example, care must be exercised in drawing useful conclusions from aggregated data. In this report, data from different studies are combined in an attempt to discover meaningful trends but the normal deviate statistical comparison is not applied between unrelated studies.

For the data presented in Table 2-2, the normal deviate test statistic is computed to be (Appendix A):

$$Z_o = 6.104 > Z_c \ (= 1.96)$$

From this it can be concluded with a 95% confidence level that air systems were more reliable than liquid systems for residential application during the HUD demonstration program. Beyond this, at the subsystem level, the collector, storage, and control subsystems of air systems were all more reliable then their liquid system counterparts. Only transport subsystem problems were statistically indistinguishable between air and liquid systems.

As previously mentioned, most studies considered for this report deal with SDHW systems only. A good discussion of the various SDHW system types (with an emphasis on freeze protection strategies) is given in Schiller [39]. Applicable reliability data are summarized and presented in Table 2-3. For each SDHW system type listed data extracted from studies 14-16 included the number of systems in each study, the percentage of systems experiencing problems, and the average number of problems per system in the study. The totals provide an aggregated picture of the relative reliability of these system types. Note that draindown has been used to describe both drainback and drainout systems. In the studies reviewed and in this report, however, draindown is used in the context of a drainout system. A draindown system isolates the storage tank and uses automatic valves to drain the collectors and piping whenever a freezing condition is sensed, or optionally, whenever the pump stops. The drained water is disposed of and is not reused. In a drainback system, the water returns to a drainback tank (whenever the pump stops) from which it is recirculated when needed. Recirculation systems pump warm fluid from storage through the transport/collector subsystems to prevent freezing.

Less than a third of the drainback and recirculation systems reported problems. Draindown, air, oil, and electrically heat-traced systems all had very

Table 2-3. Reliability Problems of Common SDHW System Types

SDHW System Type	Study 14			Study 15			Study 16			Total		
	No. of Sys-tems	Percentage of Systems with Problems	Average No. of Prob-lems/ System	No. of Sys-tems	Percentage of Systems with Prob-lems[a]	Average No. of Prob-lems/ System	No. of Sys-tems	Percentage of Sys-tems with Prob-lems	Average No. of Prob-lems/ System	No. of Sys-tems	Percentage of Systems with Prob-lems	Average No. of Prob-lems/ System
Drainback	22	32	0.36	2	50	1.00	1	0	0.00	25	32	0.40
Draindown	13	92	1.92	24	88	5.54	2	0	0.00	39	85	4.05
Recirculation	63	27	0.33	0	--	--	0	--	--	63	27	0.33
Antifreeze	29	14	0.14	48	77	2.19	18	83	1.44	95	59	1.42
Air	0	--	--	4	75	1.00	2	100	1.50	6	83	1.17
Oil	0	--	--	0	--	--	6	83	1.33	6	83	1.33
Heat-traced[b]	0	--	--	22	100	3.68	0	--	--	22	100	3.68
TOTALS	127	30	0.79	100	84	3.25	29	76	1.28	256	57	1.64

[a]Assumes top 15 systems + 1 air system were essentially trouble-free.

[b]Electric resistive heating provided to piping to prevent freezing.

high incidences of problems. More than 80% of each of these systems sustained malfunctions. Antifreeze systems had an intermediate number (59%) of problems.

In terms of the average number of problems sustained per system, drainback and recirculation systems fare extremely well (less than one problem for every two such systems). Antifreeze, air, and oil systems exhibit an intermediate level of problems (1 to 2 problems/system). Heat-traced and draindown systems had extremely high occurrences of problems (3.68 and 4.05 problems/system, respectively). The following additional points can be made:

- In study 14, 11 of 12 draindown systems had problems resulting in a 2.6% downtime. Although caution was urged in drawing meaningful conclusions based on such a small sample size, the high percentage of failures (92%) was replicated in study 15 (88%).
- The top 15 systems examined in study 15 were manufactured by companies having the most experience in actual solar installations. Installers were also the most experienced with solar installation practices and exhibited careful attention to detail and follow-up. Based upon poor reliability, the supplier of the heat-traced systems switched to a product line of antifreeze systems.
- With the exception of antifreeze systems all problems reported in study 16 were attributable to component failures. Half of the antifreeze system problems were caused by poor installation, and half were caused by inferior components.

Study 19 provided an alternative classification of SDHW systems. Systems were grouped according to whether they were packaged, contractor built, or homemade. Reliability data for these categories are given in Table 2-4. All three system types exhibited high, roughly equal percentages of problem incidences. Homemade systems had a slightly lower percentage of problem incidences, which may be because homeowners take greater pride and care in their work and also are less willing to report problems. No statistically significant difference (at 95% confidence level) exists between the problem incidences reported for the three types of systems. The observed normal deviate between the packaged and contractor-built systems was $Z_o = 1.592 < Z_c$ (= 1.96).

Table 2-4. Reliability Data of Systems Classified in Study 19

	System Type			
	Packaged	Contractor Built	Homemade	Total
No. of systems	60	46	48	154
Percentage of systems with problems	77	78	63	73
Average No. of problems/system	0.97	1.11	0.77	0.95

SECTION 3.0

RELIABILITY AND MAINTAINABILITY OF SOLAR ENERGY SUBSYSTEMS

The major solar energy subsystems are considered to be collectors, storage, transport, and controls. An array of collectors allows primary capture of solar energy. Initial accumulation and subsequent time-phased release of collected energy are provided by the storage subsystem. Delivery of energy from the collector to storage or from storage to meet a demand load is provided by the t*ansport subsystem. Collection and distribution of energy by the solar energy system is accomplished under the supervision of a control subsystem. R&M issues of the auxiliary or conventional back-up subsystem are also discussed in this section.

3.1 COLLECTOR SUBSYSTEM

The collector subsystem is defined as consisting of solar collectors and headers and connectors. A number of collector designs are commonly in use. These include air and liquid flat-plates, evacuated tubes, and tracking/ concentrating designs. In general, a flat-plate collector will incorporate the following elements: one or two transparent glazings (glass or plastic), an absorber (comprised of a substrate material and a selective or nonselective coating), insulation, gaskets and seals, and some form of enclosure to hold everything together. Evacuated tube collectors consist of an array composed of two concentric glass tubes with the space between them evacuated. Back reflectors are typically included. Concentrating collectors are of the linear type (i.e., sunlight is focused onto a straight absorber pipe) and achieve concentration either with a parabolic reflector or a Fresnel lens cover sheet. These concentrators require drive and tracking mechanisms to follow the sun. Headers and connectors consist of ducts and piping (metal or plastic), interconnections and fittings, insulation, and seals and gaskets.

3.1.1 <u>Collectors</u>

3.1.1.1 General Collector Studies

A summary of the NSDP collector problem incidences is presented in Table 3-1. Total collector problems were found to be almost evenly divided between first year occurrences and incidences during the remaining lifetime of the studies. With the exception of the earliest study (1), the percentage of systems reporting collector problems generally decreases with time for both the residential and commercial sectors. For the commercial installations, nearly two-thirds of all reported problems occurred during the first year of operation, whereas there is a more even distribution in the residential studies. The majority of problems reported in earlier residential studies (1&2) followed the initial year of service; the reverse effect is true for the later studies (3&4). This may be because of the longer service lifetime experienced by the earlier installations. Details of the various NSDP studies (1-7) follow.

Table 3-1. Summary of NSDP Collector Problem Incidences

Study No.	Length of Study Past First Year (Months)	Total No. of Systems	Percentage of Systems Reporting Collector Problems	Total No. of Systems Reporting Collector Problems	Total No. of Collector Problems Reported	First Year No.	First Year %	After First Year No.	After First Year %
1	39	110	36	40	75	29	39	46	61
2	31	246	54	134	124[a]	24	19	100	81
3	25	355	19	68	50[a]	37	74	13	26
4	8	212	13	27	38	34	89	4	11
Residential Subtotal		923	29	269	287	124	43	163	57
5	28	25	52	13	39	22	56	17	44
6	14	41	32	13	18	11	61	7	39
7	17	24	25	6	7	7	100	0	0
Commercial Subtotal		90	36	32	64	40	62	24	38
Total		1013	30	301	351	164	47	187	53

[a]It is believed that for identical systems having the same problem, the problem was only counted once (1 "total problem" but multiple "systems reporting problems") so as not to unduly inflate the problem incidences [67].

Figure 3-1 is an example of the type of information provided for the various subsystems (collectors, transport, storage, and controls) discussed in studies 1-7 [14]. The abscissa provides the total number of months for which data were collected (length of the study). Note that the reported problems have been renormalized after the first year of operation to easily allow comparison of early vs. late service lifetime failures. Problems are also categorized according to level of severity (i.e., no effect, partial shutdown, and total shutdown). The frequency and severity of subsystem problems are thus readily evident as a function of time from these graphs. This information is also conveniently tabulated for each subsystem/study and the total number of systems and percentage of systems reporting problems are also presented. The overall problem rate (problems/month), as well as the rate as a function of problem severity, is available as the slope of these frequency plots.

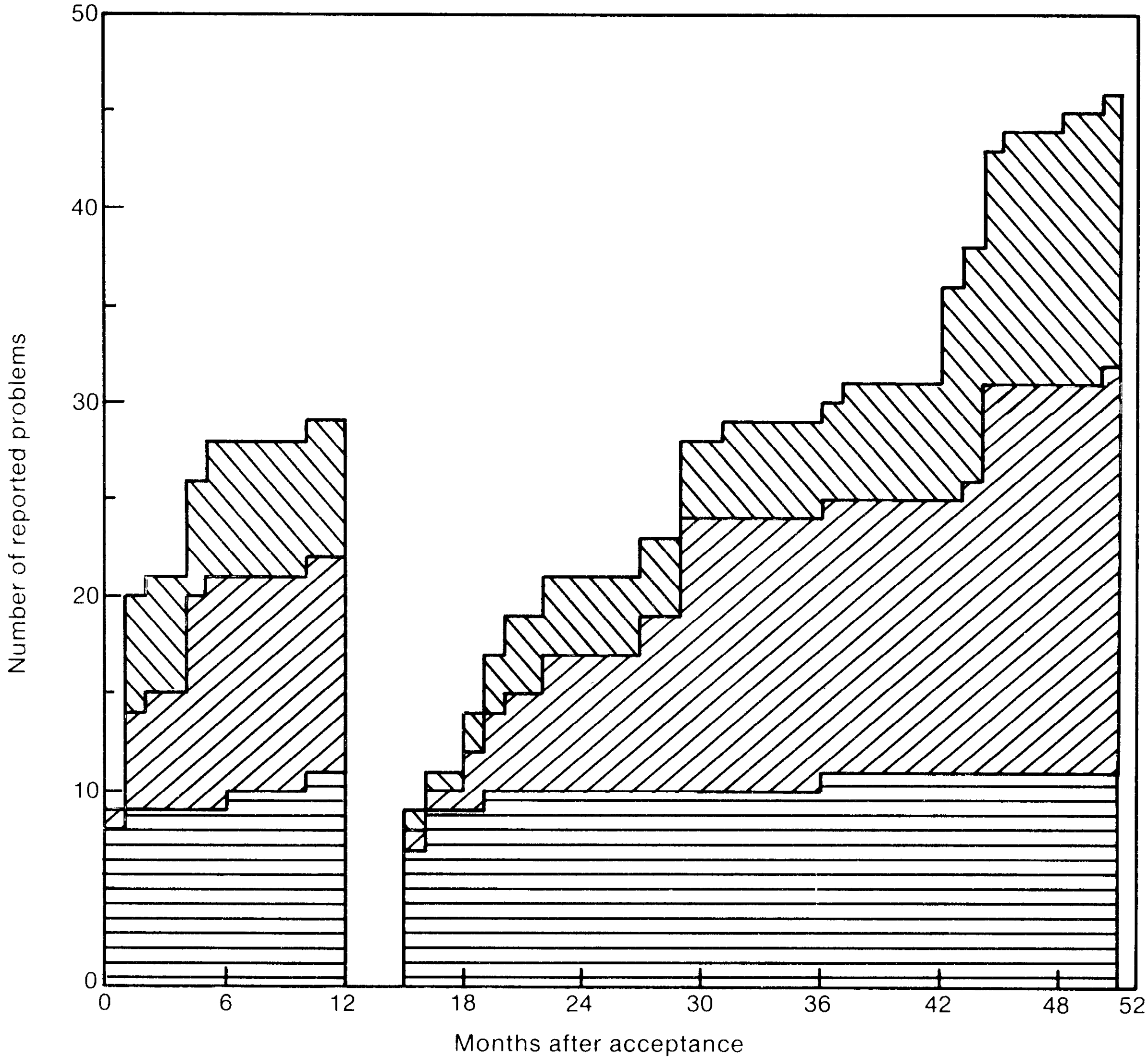
Of the subsystems considered, the largest number of problems reported by study 1 was associated with collectors. Nearly a third of these problems were severe enough to completely shutdown the system. Most problems occurred during the first year and a half of service. Minor collector problems (which only partially shut down the system or had no effect on system operation) were uniformly distributed in time (Figure 3-1). Thirty-six percent (40 of 110 systems) of the systems included in this study experienced 75 collector problems.

Study 2 also reported the collector subsystem as having the highest percentage of problems compared to other subsystems. Fifty-four percent (134 of 246 systems) of the systems in this study reported 124 collector problems. (Identical systems having the same problems were only counted as a single problem incidence, but all systems affected were tallied in terms of the number of systems reporting problems [40]. Thus, 134 affected systems reported 124 total problems.) The number of collector problems rose dramatically after the first twelve months of service; 81% of these problems occurred after the first year. Nearly a third of all collector problems were severe enough to cause the entire system to shut down.

Nineteen percent (68 of 355 systems) of the systems in study 3 reported 50 collector-related problems. This represents a substantial improvement in overall problem incidences compared to earlier studies, although the number of problems occurring during the first year of operation increased relative to the earlier studies. About three-fourths of the collector problems in this study were experienced during the first year. Problems tended to be less severe, however, with 74% resulting only in partial shutdown of the system.

In study 4, all of the collector problems either partially or completely shut down the system. Eighty-nine percent of all collector problems occurred during the first twelve months, and these generally shut down the system. Thirteen percent of the included systems (27 of 212 systems) reported a total of 38 problems.

The collector was the most problem-plagued subsystem considered in study 5. Over half (13 of 25 systems) of the systems in this study reported 39 collector problems, an average of three such problems per failed system. Most collector problems (56%) occurred during the first year of operation. The problem rate dropped from two per month during the first year to every two months during the final 28 months of monitored service.



Total systems						
Total systems						110
Total systems reporting problems						40
Percentage of systems reporting problems						36
	Legend	Total	1st yr		After 1st yr	
			No.	%	No.	%
Total problems		75	29	39	46	61
Problems not affecting system operations	\\\\\\	21	7	33	14	67
Problems partially shutting down system	////	32	11	34	21	66
Problems shutting down system	═	22	11	50	11	50

Figure 3-1. Cumulative Reported Problems--Cycle 1, Collector Problems [14]

Although collectors (along with controls) had the greatest number of problems reported during study 6, the severity of these troubles was low. Only one collector problem totaly shut down a system, and nearly two-thirds of such problems had no effect on system operation. Almost a third of the systems (13 of 41) reported a total of 18 collector problems, with two-thirds of these occurring during the first year of service.

Collector problems reported by study 7 were very mild. None were severe enough to completely shut a system down, and none occurred after the first year of operation. The problem rate was nearly one problem per failed system with 25% of the systems (6 of 24) experiencing problems.

3.1.1.2 Comparison of Collector Types

A large number of collector types are available for use in solar energy systems. Study No. 10 provides a comparison of four common designs; namely, liquid and air flat-plates, tracking/concentrating, and evacuated tube collectors. Problem incidences of these four types of solar collectors are summarized in Table 3-2. Note that the small number of systems in each category precludes any statistically significant (normal deviate test) comparison between these collector types. Two-thirds of the liquid flat-plate collector subsystems experienced failures, whereas only slightly more than a third of the air collectors reported problems. Half of the tubular collectors were affected by malfunctions, although only four such collectors were included in the study. Tracking concentrators encountered the greatest percentage of failures with nearly 86% (6 of 7) reporting problems. On the basis of the average number of problem incidences reported normalized by the number of collectors considered, a similar ranking is evident. Air, flat-plate collectors (0.63) were the most reliable, followed by tubular (0.75), liquid flat-plates (1.31), and tracking collectors (3.57).

Tracking Collectors. The types of problems that typically hamper tracking collectors and the frequency of these problems are listed in Table 3-3. Difficulties with the tracking motors and their controls were by far the most severe disadvantage of such collectors; over half of all tracking collector problem incidences were related to motors/controls. In general, failures were attributable to improper design of the tracking mechanism. Five of the seven collectors required replacement of tracking motors and control circuit boards. Minor hardware adjustments were necessary to resolve tracking and alignment problems with the remaining systems [20].

Skoda and Masters [41] studied only two tracking collector systems. Neither had been in service long enough to develop durability/reliability problems with materials. The problems that were observed occurred in the control and tracking systems. Skoda and Masters also visited two systems using evacuated tube collectors. Numerous problems were encountered related to the high temperature of materials and components during operation and stagnation. The problems included leakage, gasket hardening, tube coating discoloration and breaking, dirt in filter tubes, dimensional tolerances, manifold insulation discoloration, air entrapment, pump cavitation, and operational system control problems.

Table 3-2. Problem Incidences of 80 DOE-Sponsored Solar Energy Systems [20]

	No. of Systems	Percentage of Systems Affected	Average No. of Problems/ System	No. of Collector Manufacturers
Liquid Flat Plate	61	67.2	1.31	27
Air Flat Plate	8	37.5	0.60	3
Tracking	7	85.7	3.57	4
Evacuated Tube	4	50.0	0.75	3
Total	80	65.0	1.41	37

Table 3-3. Problem Occurrences Encountered by Tracking Collectors in Study 10

Problem Area	No. of Occurrences	Percentage of Total Reported Problems with Tracking Collectors
Tracking motors/controls	14	56
Tracking alignment	6	24
Reflector degradation	3	12
Tracking rotary joints	2	8
Total	25	100

Evacuated Tube Collectors. A review of evacuated tube collector designs is given in Graham [42]. Sixteen evacuated-tube collector installations were evaluated by Mather [25] with particular attention given to performance under cold, cloudy weather conditions. Four installations had been in operation for two winters and five more for a single winter season. The tubular design considered was found to successfully withstand hail, wind, snow, and ice without failure or damage. Wolosewicz and Vresk [6] suggest that the base failure rates of tubular and flat-plate collectors are roughly comparable (23-73 tube failures, 10^{-6}/h, vs. 11.4-114 flat-plate failures, 10^{-6}/h).

Flat-Plate Collectors. Several flat-plate collector designs [44] have been built and installed in the field. Study 9 found that 25 of 66 commercial systems reviewed (37%) reported 47 collector problems. Of these, 35 problems could be divided into five categories; namely, cover plate breakage (9), leaks (8), mechanical (7), weather (7) (wind, lightning, etc.), and freezing (4). This grouping is shown in Figure 3-2. The dozen remaining problems were attributable to such concerns as buckling, condensation, and dust accumulation on the glazing. These five main collector problem types were identified as resulting from poor design, thermal stress, and stagnation conditions.

A more detailed breakdown of flat-plate collector problem types is presented in Table 3-4. Data from six studies are assessed and combined to provide a clearer picture of why collectors failed in these studies. Over five hundred total systems reported 228 problems with flat-plate collectors. Twenty-one percent of all component problems reported in these studies were collector-related. This supports the view expressed in study 10 that "the major cause of low reliability of solar energy systems is the high frequency of collector failures" [20].

The greatest incidence of flat-plate collector troubles that occurred involved leaks (26% of all reported collector subsystem problems), damaged glazings (20%), seals and gaskets (15%), and freezing (12%). The relative ranking among the more frequently occurring failure modes (outgassing at 8% to leaks at 26%) is statistically supported but only marginally (Z_o = 1.4-2.2 vs. Z_c = 1.96). Problems with collector elements such as insulation, absorber coatings, and the enclosure box were of relatively minor impact and were not statistically significantly different from each other. The combined

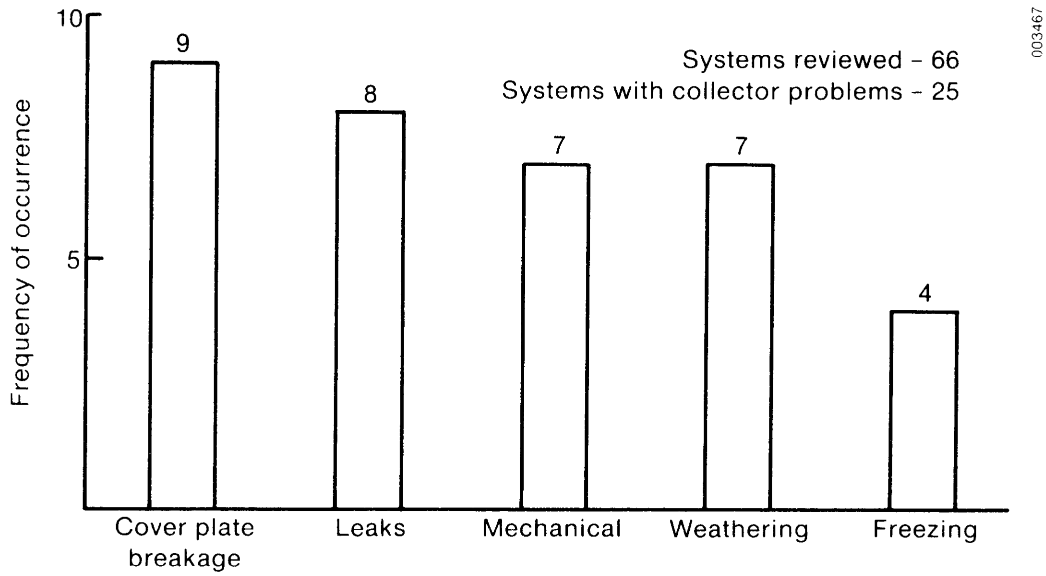


Figure 3-2. Frequency of Major Reliability Problems with Solar Collectors [19]

Table 3-4. Types of Flat-Plate Collector Problem Incidences

	Study Number						Totals	
Problem	10	11	15	16	19	20	No.	%
Freezing/burst pipe	20	--	1	2	--	4	27	12
Leaks	9	11	14	--	21	5	60	26
Seals/gaskets	18	1	--	--	15	--	34	15
Condensation/outgassing	4	--	--	--	--	15	19	8
Insulation	--	1	1	--	--	--	2	1
Glazing damage	9	1	3	1	29	3	46	20
Absorber coating	12	--	--	--	--	--	12	5
Buckling	2	--	1	--	--	--	3	1
Wind	4	1	3	1	--	--	9	4
Design/installation	2	4	--	1	--	2	9	4
Other	5	--	--	--	--	2	7	3
Total incidences	85	19	23	5	65	31	228	--
Total No. of problems reported	332	84	325	44	154	163	1102	--
Percentage of reported problems	26	23	7	11	42	19	21	--
No. of systems	69	12	100	29	177	124	511	--
Average No. of collector problems per system	1.23	1.58	0.23	0.17	0.37	0.25	0.45	--

condensation/outgassing problem was somewhat less than reported elsewhere. study 13 suggests that 20% of the collectors examined showed evidence of condensation. Outgassing was judged to be a problem in one of every eight (12.5%) systems inspected.

Reliability data on collector mounting failures are also given by study 13. Nearly a third (32%) of those roof-mounted systems considered had one or more of the following problems: insufficient attachment, contact of dissimiliar metals, wood deterioration, roofing leaks, insufficient spanners, bolts attached to sheathing only, and inappropriate choice of mounting hardware. Nineteen cases (in 170 systems) of inadequate roof support were also found.

3.1.1.3 Collector Material Problems

Closely associated with collector subsystem failures are collector material problem issues. The nature of R&M problems for materials and components used in solar collectors has been well documented in both laboratory research and field experiences. However, the frequencies of material failures have not been clearly delineated. Thus, considerable information on the kinds of material problems that can occur is available, but how often they actually occur is not readily assessable. For example, Skoda and Masters [41] identified an extensive number of performance problems for materials and components during field inspection visits to 25 active solar system installations. Although numerous problems were noted, it was also cautioned that the problems may not necessarily adversely affect long-term system performance and that further research is needed to document performance over a number of years. Nevertheless, the field survey demonstrated the existence of problems related to durability and reliability in each of the major components of one or more solar energy systems surveyed. Problems were also "identified in one or more collector subsystems with materials used for cover plates, absorptive coatings, absorber plates, insulation, seals, enclosures, and structural supports." It was also noted that "although some of the observed problems result from improper design consideration, most result from inadequate resistance of materials to the exposure conditions experienced in the solar systems."

Other reviews of material-related issues in collector subsystem R&M are available [45-47].

3.1.1.4 Summary of Collector Reliability

The following general conclusions can be stated regarding the R&M of collector subsystems:

- Collector subsystems have low reliability; 30%-50% of the systems surveyed have reported collector problems of one kind or another.
- Tracking collectors are especially failure prone.
- Problems experienced by flat-plate collectors that need to be further addressed include leaks, damaged glazings, seals and gaskets, and freezing.

3.1.2 Headers and Connectors

The collector array of an active solar energy system is connected to the storage subsystem via a piping or duct network. The number of connections needed between each collector as well as in the main piping loop and the associated insulation constitute important R&M concerns.

Manifold and interconnection problems have long been identified as significant reliability issues with solar energy systems [15-19,48]. An early Argonne Laboratory study (8) found that "collector-to-collector or collector-to-manifold connection problems have plagued about 35% of the present generation of DOE commercialization sites" [16]. A follow-up study (10) found that 31 of 80 demonstration sites (39%) were effected by interconnection failure. These 31 systems experienced 49 problems representing almost 15% of all solar component-related failures.

Header and connector problems include poor drainage (which can lead to freezing), leakage, and degraded performance due to improper design/ installation and excessive heat loss. Study 15 points out that the "proper pitch for draining and venting [is] frequently neglected in plumbing" [27]. Besides improper sloping of lines, inadequate support of pipes is also a problem. These can often be interrelated; if a manifold is not properly supported, it may deflect under its own weight, thereby counteracting any design-specified slope [16]. These problems are especially acute for nonmetallic piping. For example, of eight systems considered in study 13 that used chlorinated polyvinyl chloride (CPVC) pipes in the solar loop, 7 exhibited unacceptable distortion and waviness. This study also found that 20% of all systems had collectors that were undrainable. An equal percentage had piping that failed to meet pipe hanging standards.

Interconnection leaks can be caused by a number of factors such as hose material incompatability, hose clamp malfunction, movement caused by thermal expansion and compression, and interconnection design. Rubber hose materials must have good ultraviolet (UV) and thermal stability and be able to withstand compression set problems associated with poor clamp arrangements. An alternative to rubber is metallic hose material. Although more expensive and requiring greater design effort in terms of flexibility and thermal expansion considerations, it is generally more reliable. Metallic hose material has an estimated service lifetime of 20 years vs. 5-7 years for premium rubber hose [16].

Figure 3-3 presents the incidences of interconnection problems detected over two time periods comprising study 9. The percentage of systems experiencing interconnection problems dropped in half between these two sample sets. However, based on the normal deviate statistical comparison, the difference between the two percentages is marginally significant at best ($Z_o = 1.968$ vs. $Z_c = 1.96$). Problem incidences reported by other studies are given in Table 3-5. Note that the high incidence of failure experienced in study 11 was based on only a dozen systems. Excluding this study, general agreement is found; interconnection problems occur in roughly 10%-30% of the systems studied.

Collector manifold leaks can generally be ascribed to improper installation techniques. Of seven problems experienced during study 11, five were attributed to installation and one each to design and component failure. Study 20 assigned 40 of 41 solar loop leakage problems to installation errors. Finally, although solar loop leaks are not categorized separately from fluid passage problems, study 12 found the generic component of piping to be the second most failure-prone solar element and noted that "most leaks were due to poor design of connections to collector headers or poor installation of collector piping" [23].

Examples of degraded performance because of interconnection problems are given in study 13. It was found that 17% of the systems were piped in a direct return fashion (both the supply and return piping attach at the same end of the collector array). This can increase the likelihood of nonuniform flow in the collector array with subsequent loss in thermal performance.

Interconnection insulation problems (and resulting heat loss) were also discussed in study 13. Such problems were attributed to inadequate insulating capability (R-value too low), improper sealing of insulation (and degradation due to moisture), and UV degradation. Sixty percent of the systems used elastomer insulation. In almost all cases, UV degradation of this material was observed. Further, R-values (at installation) were generally half of the recommended levels. Drastic deterioration of paint- sealed insulation was also evident.

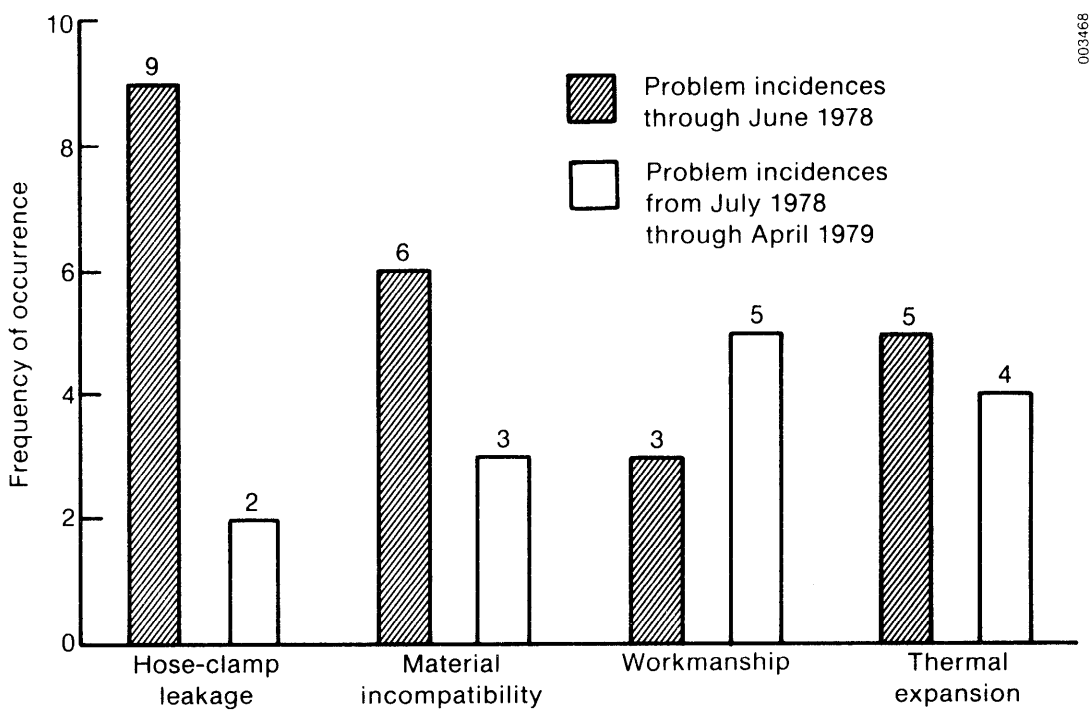


Figure 3-3. Frequency of Interconnection Problems for Solar Heating and Cooling Systems. 15 of 40 systems (37.5%) experienced problems through June 1978; 13 of 60 systems (19.7%) experienced problems between July 1978 and April 1979 [19].

Table 3-5. Interconnection Problem Incidences Reported by Selected R&M Studies

Study No.	No. of Systems in Study	Average No. of Problems/ System
11	12	0.58
15	100	0.09
16	29	0.21
19	177	0.18
20	124	0.33

3.2 STORAGE SUBSYSTEM

Because of the mismatch between available solar energy and load demand, short term storage is usually required in solar systems. In a liquid system this is typically a hot water tank; air systems usually use a bin filled with rocks. Either system can also incorporate a high latent-heat phase-change material (for example, salt hydrates) to minimize the physical dimensions of the storage unit.

3.2.1 Storage Overview

A recent R&M study asserts that:

> Before solar energy system reliability can be accurately determined, reliability data must be compiled on dampers, storage containers, air vents, and check valves. . .Of the components listed, perhaps the most critical for solar energy systems is liquid storage, due to the long-term corrosion potential. [23]

Available R&M data on storage units tend to be either aggregated data (no details are given about the variety of storage subsystems studied; hundreds of dissimilar subsystems are generically categorized as storage) or very specific (600-1000 systems that all use the identical storage subsystem). The former is characterized by the National Solar Demonstration Program data; the latter is particularly true of several of the utility demonstration programs.

An evaluation of storage system R&M data for the residential section of the NSDP is given in studies 1-4 (Table 3-6) Eighteen percent of 110 systems reported storage problems in study 1. Roughly one-third of the problems were experienced during the first year of operation; two-thirds occurred in the following 3+ years. The severity of reported problems varied with time. Those problems reported during the first year generally all shut down the system; thereafter, problems only partially shut down the system. Storage presented the fewest number of problems compared to the other subsystems (collectors, transport, and controls) considered in this study. This was also true for studies 2 and 4.

Study 2 reported 25% of 246 residential systems experienced storage-related failures. The number of problems drastically increased following the first year of operation of these systems.

In study 3 storage subsystems were second only to transport in the number of problems reported. Twenty-six percent of 355 systems experienced storage problems. Roughly half of those failures during the first year of service were severe enough to shut down the entire system. After the first twelve months,

Table 3-6. Summary of NSDP Storage Problem Incidences

Study No.	Length of Study Past First Year (Months)	Total No. of Systems	Percentage of Systems Reporting Storage Problems	Total No. of Systems Reporting Storage Problems	Total No. of Storage Problems Reported	First Year No.	First Year %	After First Year No.	After First Year %
1	39	110	18	20	21	7	33	14	67
2	31	246	25	61	100	10	10	90	90
3	25	355	26	93	83[a]	48	58	35	42
4	8	212	3	7	10	9	90	1	10
Residential Subtotal		923	20	181	214	74	35	140	65
5	28	25	20	5	9	7	78	2	22
6	14	41	22	9	13	11	85	2	15
7	17	24	13	3	5	4	80	1	20
Commercial Subtotal		90	19	17	27	22	81	5	19
Total		1013	20	198	241	96	40	145	60

[a]It is believed that for identical systems having the same problem, the problem was only counted once (1 "total problem" but multiple "systems reporting problems"), so as not to unduly inflate the problem incidences [68].

none of the storage subsystem problems completely shut down the system. This result was analogous to those in studies 1 and 4.

Only 3% of 212 systems reported storage subsystem problems in study 4. It was unclear whether this low failure rate was due to lessons learned during previous studies (1-3), or whether the relatively short time frame of this study did not provide an adequate environmental exposure duration for additional problems to occur.

Storage problems encountered during the commercial part of the NSDP are reported in studies 5-7 (Table 3-6). As with the residential systems, study 5 found that storage was the most reliable of the subsystems considered. Twenty percent of 25 systems experienced storage problems. However, the severity of these problems was small, and they had little effect on the systems.

Half of the storage subsystem problems reported during the first year of service of 41 systems included in study 6 had the effect of shutting down the system. No storage problems experienced after this time (for the remaining 14 months of the study) had any adverse effects upon system operation. Possible explanations of this time-dependent behavior are similar to those given in study 4. Twenty-two percent of the systems in study 6 experienced storage problems.

The single problem reported in study 7, which was severe enough to shut down a system was a storage failure. Thirteen percent of the 24 systems included in this study experienced storage problems of some kind.

Study 10, which also evaluated commercial NSDP systems, reports similar results to those given in studies 5-7. Twenty-three percent of 80 systems considered experienced storage container failures. This represented 5.4% of all reported problems.

Six storage-related problem incidences were reported for the 12 systems included in study 11. These ranged from three leaks to single instances of excessive pressure drop, excessive heat loss or freezing, and overheating or boiling. All of these problems were attributed to either design or installation errors. General guidelines for thermal storage design and installation are given in Cole et al. [7]. Baylin [49] presents a review of low-temperature thermal storage.

3.2.2 Tanks and Container Units

Solar storage units are typically constructed from steel, concrete, wood, or plastic (for example, polyethylene or fiberglass reinforced polyester). Lining materials include glass and stone to retard corrosion and polymers (e.g. polyethylene or polyvinyl chloride) to provide a water barrier. Test methods and results for polymeric containment materials are presented in Clark et al. [50]. Relative mean service lifetimes are estimated in Goldberg [51] as: 11 years for glass-lined tanks; nine years for stone-lined tanks; and 30 years for galvanized steel passivated by carbonate deposits.

None of the 120-gal, stone-lined tanks installed during the first year (1979) of the LILCO project (study 17) experienced failures; however, 47 tanks installed in 1980 suffered leaks. Most were attributed to defective welds during manufacture [30]. During 1982, 14 solar storage tanks reported failures [31]. LILCO also reports problems with rust originating in their steel drainback tanks [32]. The rust caused failure of the circulating pump in the solar loop. This problem has apparently been solved by using a nontoxic rust inhibitor. Only a single drainback tank had to be replaced during 1982.

TVA reports a similar occurrence of failures (8.8%) for their storage tanks [33]. A large number of potable water expansion tank failures (~9%) was also experienced. The problem was that these tanks, rated at 100 psi, were supplied with pressure/temperature relief valves rated at 150 psi. Overpressure can then cause the destruction of a butyl rubber diaphragm in the tank, causing the air side of the tank to fill with water. The resulting rusting of the uncoated steel on the air side led to burst failures. A 2.3% replacement of solar expansion tanks was also reported [33].

Adequate insulation of thermal storage units must be assured. A useful survey of insulation materials is given in Versar, Inc. [52]. HUD standards require a minimum of R-11 insulation for solar storage tanks [53]. Of 159 cases considered in study 13, 70% failed to meet this standard.

3.2.3 Storage Media

Reported failure incidences vary for different types of storage subsystems (liquid vs. air vs. phase change material). Of 100 systems included in study 15, the four air systems showed no storage problems. This is in contrast to the claim that air system storage container leakage was found to be a significant problem in study 11 [22]. Four problems (8%) were reported out of 48 antifreeze systems (two leaks and two temperature control relay faults). Out of 24 draindown systems, one leaked, while two drainback systems had no storage problems.

Similar results were found for the glycol systems in study 16. Two of the 18 antifreeze systems (11%) experienced water leaks from the solar storage tank.

Slightly improved reliability is suggested by studies 19 and 20. Ten of 154 systems (6%) and three of 124 systems (2%) had storage tank fluid leaks.

The frequency of problems with rock bin storage units used in air systems is not separately discussed by any of the R&M studies included in this report. The most common problems reported with this type of storage media based on field experiences are leakage and short-circuiting of the air path (flow above rather than through the rocks) due to poor installation or design [8]. Other problems include high parasitic losses due to excessive pressure drops through the rocks, and mold/fungus formation or dust deposits on the rock surfaces with resulting degradation in heat transfer properties.

None of the studies listed in Table 1-1 reported any R&M data for phase change material (PCM) storage subsystems. A general discussion of PCM service lifetimes is given in an NBS document [54] and an overview of phase change materials and their application is presented in Eisenbert and Wyman [55].

3.2.4 Heat Exchangers

Heat exchangers are often used between liquid solar collector loops and the storage tank in order to allow the use of a nonfreezing, low vapor pressure, and noncorrosive fluid in the collectors while inexpensive water can be used in the storage tank. In air systems an air-to-water heat exchanger is employed to heat domestic hot water. These heat exchangers are normally conventional off-the-shelf components used in a nonconventional (solar) mode.

A variety of problems have been reported with solar system heat exchangers. In an early study (10), 10% of 80 systems experienced failed heat exchangers. More recent data were more promising. Study 12 found a mean time between failures (MTBF) of 16.1 years for heat exchangers. The primary failure modes were freezing and corrosion [23].

An 11.4% failure rate for heat exchangers was found in study 18. Study 19 reported that 9% of the heat exchangers in the 154 systems in service had problems. Four heat exchangers out of 124 systems in study 20 experienced failure due to freezing. Of the six systems that used oil as the transport fluid in the PNM study (16), four reported leaks in the heat exchanger. PNM also reported that one of two air-to-water heat exchangers froze during two years of operation. The problem incidences reported for heat exchangers are tabulated and discussed further in Section 4.0 of this report. Metz and Orloski [56] present a review of heat exchangers used with SDHW systems.

3.2.5 Storage Subsystem Summary Assessment

Storage subsystem problems tend to be nonsevere, especially after systems have been "broken in" under warranty and infant mortality effects have surfaced and been corrected. The impact on system operation appears to be minimal, especially after the first year of service. Failure incidences are low for storage-related problems relative to other subsystems. Furthermore, failures tend to be tied to design, manufacture, and installation rather than inherent to the subsystem or to materials of construction. Proper attention paid to previous field experience and guidelines [5-8] should result in very reliable storage subsystems.

3.3 TRANSPORT SUBSYSTEM

3.3.1 Overview of Transport Subsystem Reliability

For purposes of this report, the energy transport subsystem of a solar energy unit is considered to include the following elements: (1) a heat transfer fluid that carries heat away from the collector subsystem for transfer to the storage subsystem; (2) fluid channels through which the transport fluid is constrained to pass, typically piping or ducting; (3) a means of fluid movement, usually pumps or fans; and, finally, (4) a means for controlling and directing fluid flow; e.g. using dampers (air systems) or valves (liquid systems). Related problems that can occur with these components include leaks, freezing, corrosion, excessive heat loss, or hardware failures (e.g. burned-out pump motors or faulty valves). In addition, a wide range of design and installation problems are possible (such as failure to specify adequate pipe insulation in the design or installation of a valve backwards).

One of the primary causes of failure of the transport distribution system is corrosion of metallic elements. Corrosion problems experienced by the residential sector of NSDP (studies 1-4) are documented in a BE&C Engineers, Inc., report [57]. Components such as piping, pumps, valves, and fittings, which have been used in the plumbing and heating industry for years without evidence of significant corrosion-related problems, failed much more frequently than expected when used in typical solar systems. This is true because solar installations are inherently different from domestic plumbing or heating installations. Some of the important differences relating to corrosion include [57]:

- Large amounts of dissolved oxygen are present in the heat transfer fluids used in most solar systems, especially open systems. The presence of oxygen allows galvanic corrosion to proceed.
- The use of components constructed from dissimilar metals in the same system in studies 1-4 was highly prevalent, thus providing the base materials for galvanic corrosion to occur. As expected, the severity of corrosion was found to be inversely proportional to the amount of ferrous material used relative to nonferrous components. This is true due to the dependence of galvanic corrosion upon the ratio of the anodic (ferrous) area to the cathodic (e.g., copper) area.
- Flow through most portions of a solar system is recirculating rather than once-through as in most domestic plumbing installations. If copper is present, this allows the build-up of a high copper ion concentration in the transfer fluid. Such ions are then readily deposited on more anodic metallic surfaces resulting in pitting.
- Although closed systems in general are less corrosion-prone than open systems, they are not totally immune. However, damage in closed systems in most cases was found to be due to improper maintenance of the heat transfer fluid and not because of improper design or installation.
- Elevated temperatures encountered in solar systems tend to support and accelerate some forms of corrosion. (Under stagnant conditions, collector temperatures in excess of 200°C can be attained.) Such temperature excursions can degrade the various glycol-based compounds commonly used for freeze protection in collector loops. When not properly maintained, the resulting acidic solution will aggressively attack metallic components.

A summary of transport-related problems experienced by NSDP is presented in Table 3-7. The findings of these projects are discussed below in greater detail.

Table 3-7. Summary of NSDP Transport Problem Incidences

Study No.	Length of Study Past First Year (months)	Total No. of Systems	Percentage of Systems Reporting Transport Problems	Total No. of Systems Reporting Transport Problems	Total No. Transport Problems Reported	First Year No.	First Year (%)	After First Year No.	After First Year (%)
1	39	110	27	30	48	16	33	32	67
2	31	246	40	98	113	44	39	69	61
3	25	355	40	141	154	100	65	54	35
4	8	212	13	28	57	52	91	5	9
Residential Subtotal		923	32	297	372	212	57	160	43
5	28	25	44	11	13	8	62	5	38
6	14	41	15	6	6	4	67	2	33
7	17	24	0	0	0	0	0	0	0
Commercial Subtotal		90	19	17	19	12	63	7	37
Total		1013	31	314	391	224	57	163	43

Study 1 reported 27% of 110 systems experienced a total of 48 transport problems. A third of these problems occurred during the first year of system operation; two thirds occurred during the subsequent 3-1/4 years of the study. Problems following the first year were generally more severe. However, the percentage totally shutting down the system increased from 29% to 71% from the first year to the balance of the study.

In study 2, the transport problem incidences increased after the first year of service, but the frequency was lower than for the other subsystems considered (collectors, storage, and controls). Forty percent of 246 systems experienced 113 transport problems. Roughly half of all transport problems did not effect system operation. The transport subsystem exhibited the highest number of problems on a percentage basis of any of the subsystems considered in study 2. More problems completely shut down the systems during the first year than during the final 2+ years of the study. The transport failure rate was the same as that of the second study; namely, 40% of 355 systems experienced 154 problems. The trend of an increased rate of overall problems after the first year was reversed with this study. Roughly two-thirds of all transport problems were reported during the first year; a third were reported thereafter.

Although transport and collectors had by far the highest percentage of problems in study 3 compared to the other subsystems, the problem rate of 13% was drastically lower than the previous three studies. Additionally, 91% of all transport problems during this study occurred during the first year of operation.

As with the residential NSDP, the transport failure rate dropped considerably with each successive commercial NSDP system study. In study 5 almost half (44%) of the 25 commercial systems experienced transport problems. Two-thirds of all problems occurred during the first year, and the percentage of transport problems totally shutting down the system decreased from 80% to 20% from the first year of operation to the next 2-1/3 years of the study.

None of the systems experienced more than a single transport problem during study 6. The failure rate decreased to 15% of 41 systems. All transport problems reported during the first year of service completely shut down the system. Furthermore, the only subsystem problem severe enough to completely shut down a system following the first year of operation was a transport problem.

No transport problems were experienced during the 2-1/4 years of study 7.

In general, during the NSDP, early studies (Table 3-7) reported relatively high incidences of transport subsystem problems (40%-45%). These occurrences decreased drastically with time (to 0-15%). This dramatic effect could be attributable to improvements in component hardware or to increased awareness of field experiences on the part of designers and installers.

3.3.2 Heat Transfer Fluids

Heat transfer fluids commonly in use in active solar energy systems include air, water, antifreeze solutions (typically either ethylene or propylene glycol), oils, and silicones. A breakdown of the frequency of use of these and other fluids in the field is presented in Figure 3-4 [58]. Desirable properties of such fluids include low viscosity throughout the range of working temperatures (to minimize parasitic power losses associated with moving the fluid), low freezing temperature (for freeze protection), high boiling temperature (to prevent excessive pressure build-up at elevated temperatures), compatibility with the other components of the system (good corrosion resistance), low toxicity, high surface tension (to minimize leakage problems), and low cost. Other desirable properties are ease of detecting leaks (air and refrigerant leaks are very difficult to detect), low scaling potential, good chemical and thermal stability, high specific heat, and ease of handling. Overviews of heat transfer fluids are given in Avery and Krall [58-60] and Sullivan [61]. References 62-66 detail research efforts that have investigated heat transfer fluid problems.

A major potential problem attributable to heat transfer fluids is failure to provide adequate freeze protection. Studies 8 and 9 discuss the instances of freezing as a function of the three most common heat transfer fluid systems: air, water, and antifreeze solution. Figure 3-5 gives the percentage of systems experiencing freezing problems as a function of system type for two consecutive winter seasons. From these studies it is apparent that the reliability of freeze protection afforded by water systems is low, although a decrease in freezing failure rates for water systems was noted from one winter to the next. In fact, water systems were seen to provide greater freeze protection during the second year of this study. The primary mode of freeze-related failures in air systems was thermosiphoning of cold air back to an air-to-water heat exchanger due to leakage of a back-draft damper. Whereas leakage rates of 5%-30% are acceptable for typical HVAC applications, documented freezing occurs in DHW solar systems when back-draft damper leakage flowrates approach 15% [21,22].

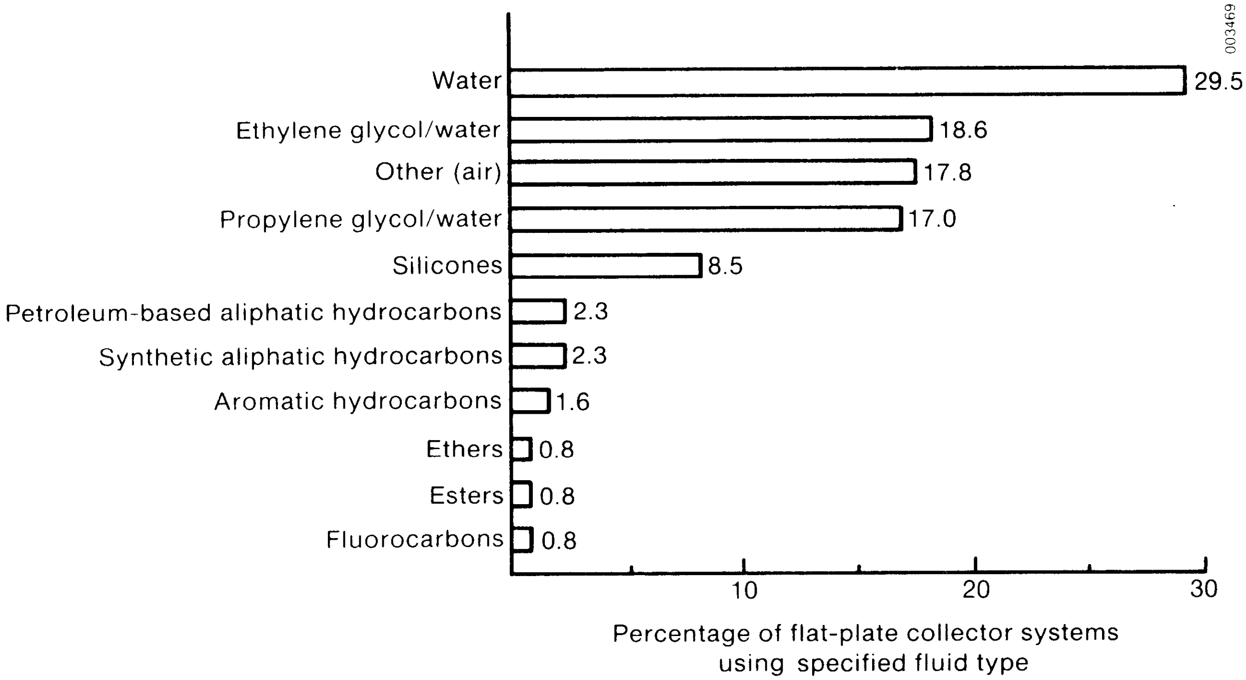


Figure 3-4. Currently Used Heat Transfer Fluids Based on Chemical Type [58]

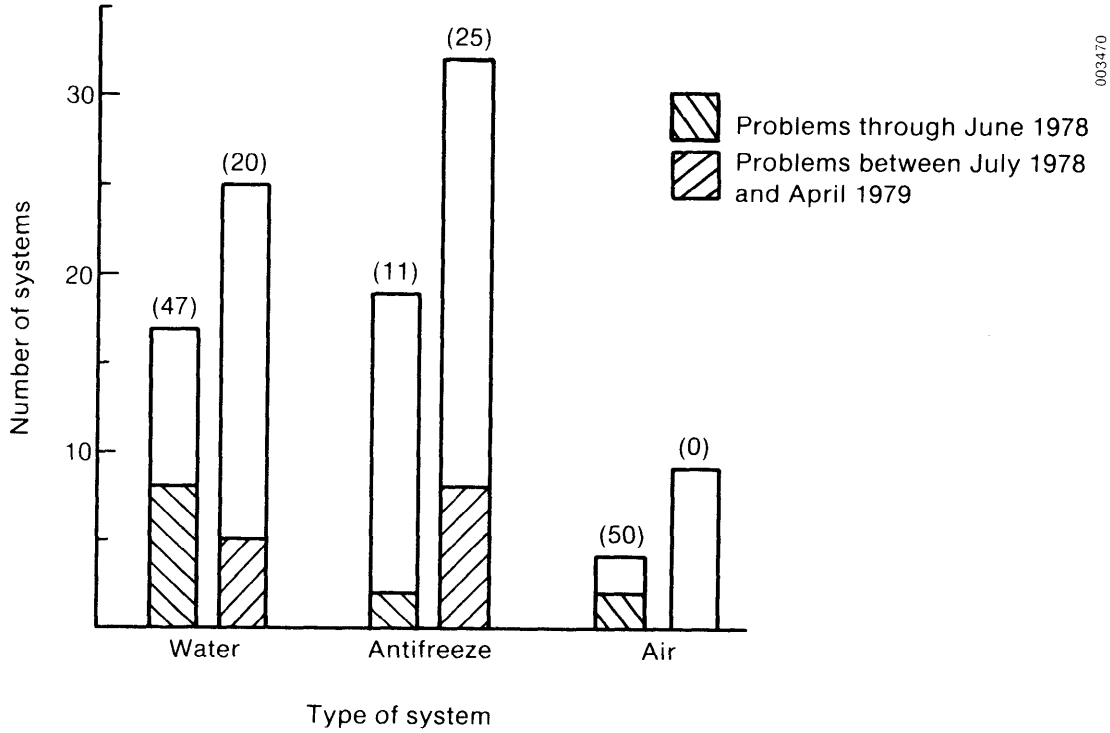


Figure 3-5. Frequency of Freeze-Related Problems for Three Types of Solar Energy Systems [17]. The height of each bar indicates the total number of systems in each category. Numbers in parentheses are the percentage of systems experiencing freeze problems.

It is noteworthy that a significant number of antifreeze systems did not provide adequate freeze protection. However, the damage resulting from such failures is less costly than freezing failures of water systems. The primary failure mechanism of antifreeze systems is also thermosiphoning of glycol solution between cold collectors and a warm heat exchanger, causing freezing of the water side of the heat exchanger.

Another potential problem with antifreeze systems is the loss of freeze protection. This can happen, for example, by dilution of the antifreeze concentration during initial installation or by automatic fluid make-up with plain water. Additionally, degradation of freeze protection properties can be caused by the working environment. Although study 15 found that only 2% of 48 antifreeze systems had an antifreeze solution that was too weak, 34% of 128 antifreeze systems in study 13 exhibited inadequate freeze protection charge. No data concerning the actual number of freeze-related failures attributable to an inadequate antifreeze concentration level are available from these studies. A number of approaches to preventing freezing for a variety of heat transfer fluids are discussed in Schiller [39], Santor [67], and Kimball [68].

Heat transfer fluids have the potential to cause corrosion of other system components. Fluids that normally afford good corrosion protection (e.g. glycol solutions) can degrade during service conditions and initiate chemical attack of pipes, collectors, heat exchangers, etc. Study 18 reports that overheating of collectors with selective absorbers caused propylene glycol to become acidic. This was identified as a major problem with the Memphis 1000 study during the summer of 1979. Thirty-nine percent of the propylene glycol systems in study 13 that had upper temperature limit shut-off control strategies (which allowed collector stagnation) were found to have acidic heat transfer fluids (pH < 6.5).

Corrosion products in the fluid can also have adverse effects upon other components. Study 17 reported that rust and other water impurities caused check valves and circulating pumps to fail.

Other heat transfer fluids may also degrade and promote corrosion. All four systems that used glycerin as the working fluid in study 13 exhibited low pH levels.

A main drawback of silicone as a heat transfer fluid is its tendency to leak due to its very low surface tension [61]. Six out of seven systems in study 13 that used silicone fluids experienced leaks. Four out of six oil-charged systems in study 16 also exhibited evidence of leakage.

In summary, although no single heat transfer fluid exhibits all of the desirable properties, most are capable of functioning properly if their limitations are recognized and taken into consideration during system design, installation, and operation.

3.3.3 Fluid Passageways

Fluid passageways provide the means for allowing the heat transfer fluid to circulate between the collector subsystem and the storage subsystem. This refers to duct work for air systems and piping for liquid systems. Study 12 found piping to be the second most failure-prone component of solar collection systems (after controls). A failure rate of 0.12/yr (MTBF of 8.3 yr) was reported, which is more than three times greater than previously published [5] rates based on other nonsolar mechanical systems. Based on this finding and the correlation between piping failures and leaks, study 12 recommended that "more study should be directed to the area of leakage" [23].

Study 14 also found leaks to be the second most prevalent problem encountered (after controllers). Of the systems considered, 7.3% leaked from causes other than freezing. A similar failure rate (6.6%) was revealed by study 18.

The vast majority of the piping problems experienced in the field have been attributed to improper installation. Roughly a third of the systems included in study 20 experienced leakage problems, and 98% were traceable to poor installation. Other problems with pipes reported in this study were inadequate/improper pipe insulation (2.4%) and frozen pipes (1.6%). These were also installation-related mishaps. Of 18 piping/ducting problems found with the 12 systems documented in study 11, all were again assigned to installation. Problems (and the number of occurrences) included leaks (6), poor insulation (5), improper sizing (2), noise (1), freezing (1), excessive heat loss (1), installation quality (1), and aesthetics (1). Finally, study 15 suggests the same conclusion. Leaks (21), improper pitch of piping in draindown systems (15), and insulation problems (82) were all generally regarded as manifestations of faulty installation.

Thus, many problems with fluid passageways have been documented. Consequently, attention has been called to this component as an important reliability issue deserving further consideration. On the other hand, strong evidence suggests that most fluid channel failures can be eliminated by improved installation practices.

3.3.4 Fluid Movement

The driving force for fluid circulation in solar energy systems is typically provided by fans for air movement and pumps (usually centrifugal) for liquid flow. Air handlers have been generally reliable components, although malfunctions have been reported. Study 15 relates a problem with excessive noise in the four air systems studied. Motor burnout occurred with three blowers in seven air systems included in study 11. However, two of these failures derived from poor design specification of a low-temperature class A motor where a high temperature fan motor was required. Only one air handler problem was reported for the eight systems in study 10.

Pump problems exhibit an interesting correlation between the frequency of problems encountered and the time during which the studies were conducted. Table 3-8 lists the relevant studies chronologically and provides the percentage of pump failures. The trend of the percentage of system reporting pump failures with time is clearly evident. As can be seen, early studies indicate high percentages of failures (20%-35%), whereas later studies show much higher reliability. The increase between 1975 and 1978 is not believed to be due to an increase in problem incidences during this period but rather to a refinement in problem detection and reporting techniques. Possible explanations for the decrease in pump problem incidences after 1978 include improved hardware, improved installation practices based upon increased awareness of field experiences, and a change in the definition of "problems" to only include component (hardware) failures.

Similiar conclusions can be drawn on the basis of the percentage of systems reporting pump problems per year (normalized by the number of years for each study). The higher problem rates found in studies 15 and 11 in Table 3-8 are both for one-year studies in which the nature of infant mortality could be expected to bias these results.

Further discussion of pump-related results are as follows:

- In study 19, air fans were included in the reported pump problem category. Fluid movement was rated as the second highest problem area (after controls) of 177 systems surveyed.
- If installation and noise problems are eliminated from consideration in study 15, only 14% of the systems experienced pump failures. Furthermore, six out of seven instances of overheated pumps occurred with heat-traced collector systems. These systems were retrofitted with antifreeze solutions at the manufacturer's recommendation. Exclusion of these problems results in an 8% problem percentage for this study.

Table 3-8. Chronology of Pump Problem Rates

Study No.	Dates of Study	Percentage of Systems Reporting Pump Problems	Percentage of Systems Reporting Pump Problems/ Year
19	1973-78	21.0	4.2
15	1975-76	23.0	23.0
10	1976-80	35.0	8.8
11	1978-79	33.0	33.0
20	1978-80	11.3	5.7
17	1978-82	5.4	1.4
18	1979-82	4.4	1.5
14	1981-82	1.5	1.5

- The problem incidence percentage given by study 10 was based on a total of 80 systems. This translates to 39% of the nonair systems that experienced pump problems. Details of the severity of pump problems were not given.
- As with study 19, study 11 also included fans in the reported pump failures. Two-thirds (6) of the pump problems were component-related although two of these included such designations as "noise" and "serviceability."
- The majority of the pump problems associated with study 20 (11 of 14) were component/manufacturer-related. Problems included air entrapment, jammings, worn impellers, casing leaks, and overheating.
- Thirty-four circulating pumps were replaced in study 17 by December 1980; failures were due to low voltage controller output problems and were not directly related to pump component hardware. The pump problem incidence rate was 0.3% during 1982 [31].
- Both of the pump failures reported by study 14 occurred in recirculation systems.

A recent instrumented study (12) found the failure rate for pumps to be quite low. The estimated failure rate was 0.07 failures/year/pump, corresponding to an MTBF of 39.1 years. This agrees well with an earlier estimate of a 30-year service lifetime for pumps [51].

3.3.5 Fluid Control Hardware

Fluid control hardware includes vents and dampers for air systems and vents and valves for liquid systems. These components serve to direct flow, provide pressure, vacuum, and temperature protection, permit proper draining, and (in hot water systems) allow mixing of heated water with the inlet cold water supply to satisfy load demands. In study 10, 50% (4 of 8) of the air systems experienced problems with dampers; 26% (19 of 72) of the liquid systems reported valve problems. Another study (20) found an 8.9% combined percentage of systems experiencing problem incidences for valves and dampers.

Valves and dampers can be further classified according to the function they perform. Such a breakdown by study is given in Table 3-9. Problem incidence percentages range from low (2.5%-3%) for tempering valves to intermediate (18.5%) for backflow preventers. The relatively high problem frequencies reported by study 13 were all design/installation related in which specified components were omitted. The highest occurrence of problems in both studies 11 and 15 were those associated with omission of vents and valves. These were generally traceable to design and installation errors. Study 20 did find a large percentage of manufacture-related problems, although the overall incidence of fluid control hardware problems was less than 7% of the total maintenance required by solar components.

Automatic powered valves (e.g., those used in draindown systems) were found to be very reliable by study 12. A failure rate of 0.07 failure/year (MTBF of 13.6 years) was determined. This was in contrast to the high failure rate of draindown valves reported by study 14 in which 13 systems experienced nine draindown valve failures in a year. Recent laboratory testing at SERI tends to support the latter study [69].

With the exception of the need for high quality back-draft dampers to prevent heat exchanger freezing in air systems, fluid control hardware is evidently fairly reliable. As with other transport subsystem components, the majority of problems appear to be preventable by proper design and installation practices. The reliability of draindown valves should be further investigated.

3.4 CONTROLS SUBSYSTEM

High failure rates with controls subsystem components have been frequently experienced in the solar industry since its inception [30,36]. Part of the reason for this is the inherent complexity of solar energy systems. Complications arise because the various modes of operation depend upon time-varying insolation rates and sporadic demands by the storage and collector subsystem. Additionally, control decisions must be made on the basis of small temperature differences. Finally, solar system control must be interfaced with the control strategies of the conventional/auxiliary heating and cooling systems [70].

Controller components considered in this section include the control hardware unit (controller), control strategy, sensor leads, and temperature sensors. Control valves were discussed in Section 3.3.5. Causes of control failures include design, specification, and installation of the controller; set point selection and logic, specification, calibration, installation and location (placement) of the sensors, thermal degradation of the sensors, and environmental effects on the controller. Potential harmful effects of control failures include freezing [15,16,36], high temperature degradation of trans-port fluids [33], damage of other components such as collectors or pumps [30], degradation in performance by loss of collectable energy, unnecessary use of auxiliary energy [70], excessive thermal losses, uneconomical pump operation, and thermal degradation of the storage tank, pump, and other components from excessive thermal excursions.

Table 3-9. Valve and Damper Problem Summary

Study No.	Valve/Damper Problem Type (Percentage of systems experiencing this problem): Air Vent	Tempering Valve	Pressure/ Temperature	Check Valve	Backflow Preventer	Problem Area (Percentage of systems experiencing this problem): Omitted	Sticking	Leaks	Relieved Too Often	Fault in Valve	Problem Responsibility (Percentage of valve/damper problems): Design	Installation	Manufacture	Other
11	--	--	--	--	--	42	17	17	--	--	44	33	22	--
13	20	--	30	--	--	--	--	--	--	--	--	--	--	--
15	--	--	--	--	--	6	5	3	3	4	--	--	--	--
16	--	--	14	--	--	--	--	--	--	--	--	--	--	--
17	--	2.5	--	--	--	--	--	--	--	--	--	--	--	--
18	11.9	3	2	6	18.5	--	--	--	--	--	--	--	--	--
20	--	--	--	--	--	--	--	--	--	--	--	18	73	9

3.4.1 Overview of Control Problems

Table 3-10 presents problem incidences for the non-NSDP studies that have only a general classification of control problems. As can be seen, fairly high frequencies of control problems are reported. More than one out of every two systems experienced control problems in study 10, representing 26% of all solar system failures reported. The PNM study (16) sited faulty controllers and temperature sensors as the most frequently reported problem. This was also the case with study 19. The main conclusion drawn by study 20 was that "solar control systems are the weakest link in an SDHW system. More durable control systems than those in use in the late 1970s are needed" [36]. In this study, the percentage of solar-related problems due to controls was the same as that reported by study 10. Fifty-nine percent of control failures were attributed to component design and/or assembly mistakes during manufacture.

Control problems were also prevalent during both the residential and the commercial parts of the NSDP. Table 3-11 summarizes these general findings. All control problems reported by study 1 affected system operation. (Roughly half partially shut down the system and half completely shut down the system.) The more severe problems (total shutdown) were uniformly distributed throughout the study, whereas the minor occurrences did not arise until after two years of service. Most systems that reported control problems experienced only a single malfunction. (23 systems reported 25 problems.)

Study 2 exhibited the highest incidence of problems of the residential NSDP cycles. Ninety-three systems (38%) reported 118 instances of control problems. The majority (81%) of those problems that totally shut down the system occurred after the first year and a half of operation.

Controls were the most reliable of the subsystems considered in study 3. Each system that experienced control difficulty had only a single occurrence of trouble (47 out of 355 total systems reported 47 control problems); most problems (83%) took place during the first year of service.

The problem rate of controls in study 4 was very low; 5% of 212 systems experienced only 18 control problems. Furthermore, no control-related mishaps completely shut down a system. Almost all (94%) control problems occurred during the first year of service, and none of these adversely affected system operation after the first year (during the last 8 months) of the study.

Table 3-10. Control System Problem Incidences

Study No.	Average No. of Control Problems per System	Percentage of all Reported Solar Problems
10	0.54	26
16	0.24	--
19	0.41	--
20	0.33	25

Table 3-11. Summary of NSDP Control Problem Incidences

Study No.	Length of Study Past First Year (Months)	Total No. of Systems	Percentage of Systems Reporting Control Problems	Total No. of Systems Reporting Control Problems	Total No. of Control Problems Reported	First Year (No.)	First Year (%)	After First Year (No.)	After First Year (%)
1	39	110	21	23	25	6	24	19	76
2	31	246	38	93	118	45	38	73	62
3	25	355	13	47	47	39	83	8	17
4	8	212	5	11	18	17	94	1	6
Residential Subtotal		923	19	174	208	107	51	101	49
5	28	25	52	13	26	18	69	8	31
6	14	41	37	15	18	16	89	2	11
7	17	24	8	2	3	1	33	2	67
Commercial Subtotal		90	33	30	47	35	74	12	26
Total		1013	20	204	255	142	56	113	44

The trend toward improved reliability with each succeeding study was evident with the commercial NSDP Projects as well as with the residential cycles (Table 3-11). As may be expected, due to the higher complexity of commercial control systems relative to those in residential use, a higher overall problem incidence percentage was encountered. In study 5, over half (52%) of the systems suffered control problems. Many of these were repeat instances; systems that reported problems averaged two problems each (13 systems had 26 problems). Of those control problems that affected system operation, 79% occurred during the first year. Only a single problem in the last 2-1/3 years of the study partially shut down a system, and only 1 of 26 reported control problems was severe enough to completely shut down a system.

Controls had the highest frequency of problems of those subsystems considered in study 6 (37% of 41 systems experienced 18 problems). As with study 5, control problems were not severe; only one instance completely shut down a system. Eighty-nine percent of all malfunctions occurred during the first year of the study.

Study 7 had the lowest occurrence of control problems of the commercial sites (8%). Only three problems were sustained, and none of these affected system operation.

In general, fairly high incidences of problems were encountered with control subsystems in the NSDP studies. However, the level of severity was low. Reliability of control subsystems tended to improve with time for both the residential and the commercial sectors.

3.4.2 Controller Hardware

The percentage of systems considered in various studies that experienced controller hardware problems are listed in Table 3-12. Incidence percentages are given as a function of controller problem type. The majority of problems encountered appear to be with defective components.

Studies 8 and 9 provide an indication of how controller reliability improved between initial system operation and later service. Problem frequencies both due to design and due to defective components decreased by roughly 50% between 1976-78 and 1978-79. During the same time spans, the overall control subsystem showed an improvement from 53% to 27% in the percentage of systems experiencing controls problems. However, the percentage of control subsystem problems attributable to controller failures (design or defective component) showed an incremental increase from 57% to 64% (21 controller problems of 37 total control subsystem problems vs. 18 of 28). The frequencies of control subsystem reliability problems reported by these studies are shown in Figure 3-6.

Controller hardware evidenced the highest problem rate in study 11; design and control settings were secondary effects.

Controllers were by far the most failure-prone component of the 16 solar systems investigated in study 12. A failure rate of 0.24 failures/year (MTBF of 4.1 years) was experienced. This theme was recurrent in other studies.

Table 3-12. Percentage of Systems Experiencing Controller Problems

Study No.	Total	Design	Component	Settings	Installation	Other
8&9[a]	53(27)	38(20)	15(8)	--	--	--
11	42	8	25	8	--	--
12	63	--	--	--	--	--
14	7	--	--	--	--	--
15	33	--	26	5	2	--
17[b]	30(8)	--	30(8)	--	--	--
18	5	--	5	--	--	--
20	14	--	12	--	--	2

[a]The first number is for 1976-6/78; the number in parentheses is for 7/78-4/79

[b]The first number is for 10/78-12/80; the number in parentheses is for 1982.

For example, study 15 suggested that "controllers produced the most frequent problems of all components, and most of these problems were due to failures inside the controller [box]" [27]. Problems were sustained by 30% of the original controllers used in study 17. Most of these failures were caused by a low voltage output which adversely affected the solid state circuitry of the units [30]. More recently, controllers continue to fail in that program but at a reduced frequency (8%) [31].

Controllers were also found to be the least reliable solar component in study 20 which further suggests that "solar control system failures . . . indicate that controls need reliability-related research" [36]. An account of recent laboratory testing of SDHW control systems is provided by Farrington and Myers [71].

3.4.3 Temperature Sensors

Table 3-13 summarizes sensor problem rates analogous to Table 3-12 for controllers. Problems with temperature sensors are nearly as prevalent as controller malfunctions. Studies 14, 15, and 18 report nearly identical overall problem incidence percentages for sensors (6%-7%). The other studies listed show reduced, although substantial, sensor problems relative to controllers.

Studies 8 and 9 reported early service life sensor problems accounting for roughly half of all reported control subsystem difficulties; later data showed sensors representing only a third of all such problems. This was primarily due to a dramatic improvement in the reliability of sensor calibration.

Another problem has been the use of poor quality, inexpensive thermistors by controller manufacturers. Recent testing [71] of 3000-ohm and 10,000-ohm thermistors commonly used in the field found these sensors to be adversely affected by temperatures experienced during stagnation conditions. Failures of these sensors were attributed to their inferior quality and construction. It was felt that an incremental increase in price would result in dramatic improvements in reliability of these elements.

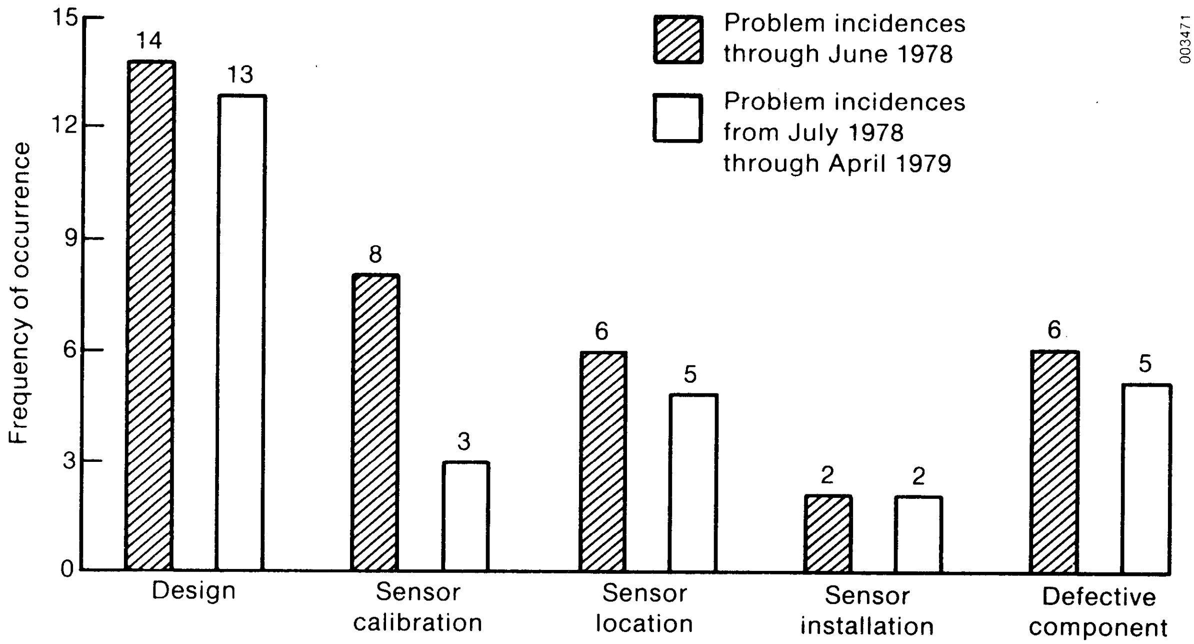


Figure 3-6. Frequency of Control System Reliability Problems [19]

Table 3-13. Sensor Problem Incidences (%)

Study No.	Total	Installation	Location	Calibration	Faulty Sensor
8&9[a]	40(15)	5(3)	15(8)	20(5)	--
11	25	8	17	--	--
14	7	--	--	--	--
15	7	4	--	--	3
17[b]	3	--	--	--	--
18	6	--	--	--	--
20	13	6	--	--	7

[a]The first number is for 1976-6/78; the number in parentheses is for 7/78-4/79.

[b]1982 data.

In general, sensor placement and installation are seen to be more critical than inherent faults with the component itself. Study 20 notes that most of the installer-caused control failures are due to improper attachment or abuse of the sensors. Although study 13 found that most sensors were properly installed, both studies agreed that factory installation of sensors is greatly desirable for improved component reliability.

3.5 AUXILIARY SUBSYSTEM

The auxiliary subsystem in an SDHW installation provides back-up water heating capability to meet load demands that cannot be met by the solar collection and/or storage subsystems. Typically, components include some form of heating element (gas flame, electric resistance heater, etc.), some form of control, and perhaps a secondary storage tank. The small amount of R&M data comparing auxiliary and solar components that could be found in the literature is discussed below.

Of 100 systems considered by study 15, a single instance each of a failed electric heating element and a failed electric heater thermostat were reported. Similar high reliability was experienced in study 18. A 3% replacement rate of heating elements in auxiliary storage tanks was sustained through June 1982 in this study.

With the exception of controller and collector fogging/frosting problems, study 20 found solar components exhibited roughly the same rate of maintenance as the back-up system. Of 124 SDHW sites monitored over a collective 199 years, ten element burnouts, four circuitry problems, and three leaks affected auxiliary subsystems. Eighty-two percent of these problems were component-related, 12% were due to improper installation, and 6% were of other or unknown origin. The number of back-up system failures (17) were comparable to the failure frequency of other components such as pumps (14), valves and vents (11), collectors (excluding frosting and fogging) (16), and heat exchanger freezing and storage tank leaks (7). Study 20 concludes that the "overall maintenance requirements . . . indicate that solar systems are almost up to par with conventional DHW systems." Almost half (48%) of those sites considered had no instances of solar-related maintenance. An important distinction is pointed out; however, namely that solar components had only been in service during this study for 1-3 years, whereas the conventional components had been in use for 1-10 years.

SECTION 4.0

COMPARISON OF RELIABILITY OF SOLAR COMPONENTS

The R&M issues associated with individual solar components and subsystems have been discussed in the preceeding sections of this report. In this section, aggregated problem incidences of various solar elements will be considered to provide an intercomparison and ranking of the relevant solar system constituents.

For over 1000 systems included in the NSDP (studies 1-7) operating between 1975-80, the collector and transport subsystems were found to be the most failure prone (Table 4-1). Approximately 30% of all systems reported problems with these subsystems. The percentage of systems encountering controller and storage subsystem problems was approximately 20%. Almost 60% of all systems experienced troubles of some kind. These problems were due to

> . . . equipment failures, design mistakes, or installation errors. In some projects only one type of problem occurred: for example, some collectors failed in otherwise well-designed and well-installed systems. But in many other cases, equipment, design, and installation problems have been mutually aggravating, with defective hardware improperly installed in bad systems. [38]

With the exception of storage, problems at the subsystem level were nearly evenly divided between start-up occurrences and problem incidences after the first year of operation.

In considering the HUD residential NSDP incidences of problems as a function of air vs. liquid systems for heating and hot water (Table 2-3), Freeborne and Mara [38] report that for air systems the transport/distribution subsystem was the most failure prone (42% of failures) compared to collectors (23%), controls (21%), and storage (14%). For liquid systems, collectors were the most problem-susceptible subsystem (31% of failures) with transport (25%), storage (22%) and controls (22%) being slightly more reliable.

Study 10 provides a detailed ranking of component failure for 80 commercial solar heating and cooling systems (Table 4-2). It was found that the combined problem occurrences for collectors, controls, interconnections, pumps, valves, and storage containers comprised 95% of the system failures. The remaining failures were caused by the other components listed in Table 4-2. Overall, components failed in 52 of the 80 systems considered. Every failed system experienced at least one collector problem. In general, there is a one-to-one correspondence between the ranking based on percentage of systems affected by failures and the average number of problems per system in this study.

Although not all components listed in Table 4-2 were assessed by study 12 (notably lacking were collectors and storage), general agreement is found between those components common to studies 10 and 12. In the latter, controls were the most failure-prone component of 16 monitored solar systems. Piping (interconnections) was the second most failure-prone component. Pumps, valves, and heat exchangers were shown to be very reliable and had

Table 4-1. **Comparison of Subsystem Problem Incidences Reported for 1013 System Included in the NSDP** [14]

Subsystem	Percentage of Systems Reporting Problems	Total No. of Systems Reporting Problems	Total No. of Problems Reported	First Year		After First Year	
				(No.)	(%)	(No.)	(%)
Collector	30	301	351	164	47	187	53
Transport	31	314	391	224	57	163	43
Storage	19	188	241	96	40	145	60
Controls	20	204	255	142	56	113	44
Totals	59[a]	598[b]	1238	626	51	608	49

[a]Source: Freeborne and Mara [38]

[b]59% of 1013 total systems.

Table 4-2. Ranking of Component Failures in 80 Commercial Solar Heating and Cooling Systems from Study 10 [20]

Component	No. of Problems Reported	Percentage of Total Failures	Percentage of Systems Affected	Average No. of Problems/System
Collectors	113	34.0	65	1.41
Controls	86	25.9	54	1.08
Interconnections	49	14.8	39	0.61
Pumps	28	8.4	35	0.35
Valves	19	5.7	24	0.24
Storage containers	18	5.4	23	0.23
Heat exchangers	8	2.4	10	0.10
Dampers	4	1.2	5	0.05
Chillers	4	1.2	5	0.05
Heat pumps	2	0.6	3	0.02
Air handlers	1	0.3	1	0.01
Total	332	100.0	65	4.15

> . . . failure rates comparable to other mechanical system applications. Solar energy system controllers are the least reliable but still fall within the range of failures exhibited by other mechanical systems. However, piping leaks on solar energy (systems) occur at three times the rate of other mechanical system applications. [23]

The failure rates and MTBF for those components studied are presented in Table 4-3. It is important to note that these results are for a small sample size (16 systems) tested over a very short time period (1 year) and they are indicative of trends at best. The failure rate and MTBF are related as:

$$\text{MTBF} = 1/\text{failure rate} .$$

The problem incidences for a number of applicable studies have been incorporated in Table 4-4. Study 17 (LILCO) and 18 (TVA) were not included in this tabulation for several reasons. First, information contained in these studies tended to be raw, unanalyzed data not easily categorized into component classification. Second, failures were multiply counted; e.g., a large number of storage tanks were replaced for the same reason/failure in the TVA study. Finally, synergistic effects confounded the problem categories. For example, controllers caused 34 pump failures in the LILCO study.

From Table 4-4, it can be concluded that piping/ducts, controls, and collectors have relatively high percentages of problem incidences. Pumps and fans and valves and dampers are intermediately reliable. Storage units and heat exchangers apear to be the most reliable solar components.

It should be reemphasized that the diverse manner in which solar R&M data have been defined, gathered, analyzed, and reported in the literature has made it difficult to quantify many specific R&M issues. Further, available information is limited and fragmented, preventing a complete and concise understanding of the overall state of solar R&M. However, general trends and relative rankings can be established.

Table 4-3. Failure Rates and Mean Times Between Failures for Solar Components Considered in Study 12

Component	Failure Rate (failures/year)	Mean Time Between Failures (years)
Controls	0.24	4.1
Leaks	0.12	8.3
Valves	0.07	13.6
Heat exchangers	0.06	16.1
Pumps	0.07	39.1

Table 4-4. Problem Incidences Reported for Solar Components by Applicable R&M Studies

Component	Study No.								Totals	
	10	11	12	14	15	16	19	20	#	%
Piping/ducting	49	18	5	10	136	9	28	46	301	26.1
Controls	86	8	10	22	40	7	63	41	277	24.0
Collectors	113	19	--	--	23	5	69	31	260	22.6
Pumps/fans	29	9	4	3	23	2	32	14	116	10.1
Valves/dampers	23	9	4	14	21	4	--	20	95	8.2
Storage	18	6	--	--	7	2	31	4	68	5.9
Heat exchanger	8	--	4	--	--	5	14	4	35	3.0
Total	326	69	27	49	250	34	237	160	1152	100.0
No. of systems	80	12	16	137	100	29	154	124	652	--
Percentage of systems affected	65	100	--	--	--	--	73	52	--	--
Average No. of problems/system	4.08	5.75	1.69	0.36	2.50	1.17	1.54	1.29	1.77	--

SECTION 5.0

CONCLUSIONS

The diverse manner in which solar R&M data has been defined, gathered, analyzed, and reported in the literature has made it difficult to quantify many specific R&M issues. Further, available information is limited and fragmented, preventing a complete and concise understanding of the overall state of solar R&M. However, general trends and relative rankings can be established. The following conclusions and recommendations have been formulated based upon the evaluation and assessment of historical R&M data found in the literature.

A comparison of the reliability of solar systems revealed that

- Based on a small number of comparative systems, DHW-only systems are relatively more reliable than combined SH + DHW systems
- Liquid systems are, in general, less reliable than air systems. However, it should be noted that the nature of air systems makes failures difficult to detect. (Levels go unnoticed and do not cause damage.) Such problems can only be characterized in terms of a degradation in system performance.
- Of the liquid systems, drainback and recirculation systems are fairly reliable, antifreeze and oil systems are intermediately reliable, and draindown systems and systems with electric resistance heating to prevent freezing are the least reliable of the systems studied.

Evaluation of solar subsystems disclosed that

- Collector subsystems have low reliability; 30%-50% of the systems surveyed reported collector problems of some type
- Tracking collectors are especially failure prone
- Problems experienced by flat-plate collectors that need to be further addressed include leaks, damaged glazings, seals and gaskets, and freezing
- Manifold and interconnection problems continue to be significant reliability issues with solar energy systems
- Storage subsystem problems tend to be nonsevere, and the impact on system operation appears to be minimal
- Proper attention paid to design and installation guidelines should result in very reliable storage subsystems
- Although no single heat transfer fluid exhibits all of the desirable properties such a fluid should have, most are capable of functioning properly if their limitations are recognized and taken into consideration during system design, installation, and operation

- Many problems with fluid passageways have been documented but strong evidence suggests that many fluid channel failures can be eliminated by improved installation practices
- Control subsystems experience fairly high incidences of problems although the level of severity tends to be low
- Temperature sensor placement and installation are more critical than inherent faults with the component itself.

Concerning the relative reliability of solar components, it can be concluded (Figure 5-1) that

- Piping/ducts, controls, and collectors exhibit relatively poor reliability and require further R&M research. Although piping and ducts exhibited the lowest reliability of the solar components considered (Figure 5-1), problems tended to be installation-related (avoidable) and generally less severe (typically easily repairable leaks) than problems with other components
- Pumps and fans and valves and dampers are intermediately reliable
- Storage units and heat exchangers appear to be the most reliable solar components.

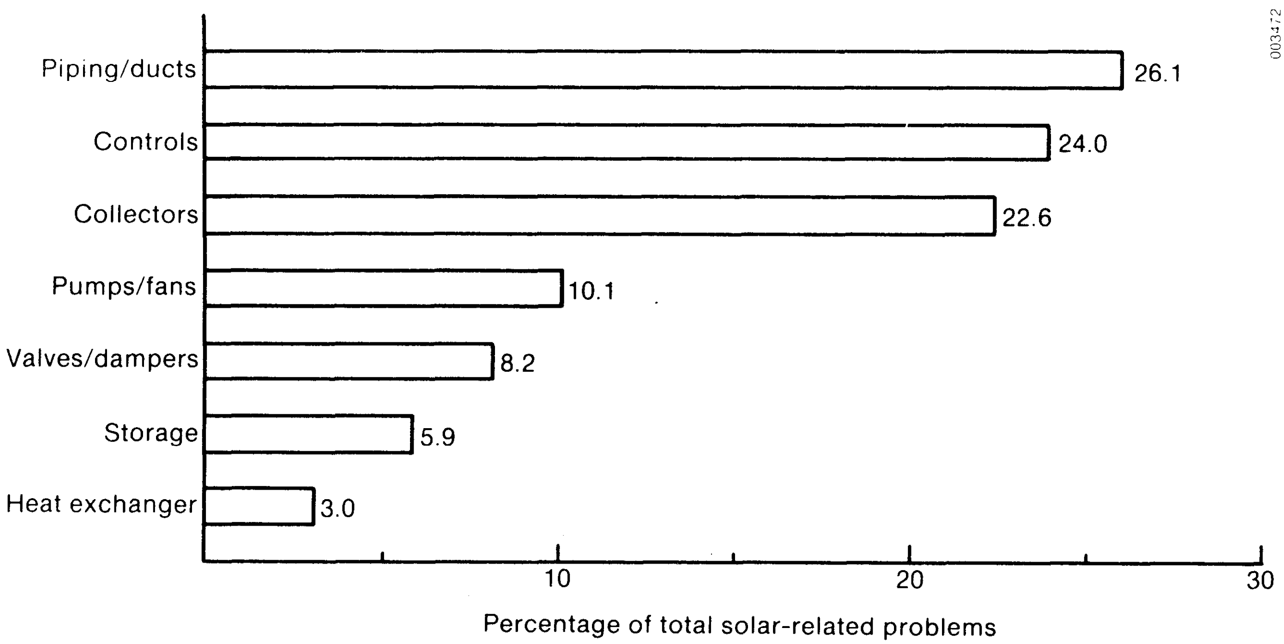


Figure 5-1. Relative Reliability of Solar Components Based on Aggregated Data (652 systems) from Table 4-4)

From data reported for over 1000 NSDP insallations (Table 4-1):

- Total system problems were equally divided between "first year" (51%) and "after first year" (49%) occurrences
- At the subsystem level, storage problems were more frequent following the first twelve months of operation
- Transport and controls subsystems were slightly more failure-prone during the first year of service compared to later operation.

Historically, the incidence of solar-related R&M problems has been extremely high. This has significantly contributed to the failure of active systems to compete as an effective energy device in the residential and commercial markets and has given the solar industry a poor reputation. However, indications exist that solar R&M has improved with time. Moreover, additional advances are readily obtainable especially in terms of system design and installation. This result is supported by a recent extension of study 14, which found 36% of all problems were installer-related [72]. It was concluded that

> . . . installation-related problems are the most frequent cause of improper system operation. In all probability, this type of problem should decrease as existing installers learn from their mistakes and new installers, hopefully, will also benefit from the growing base of experience. [72]

SECTION 6.0

REFERENCES

1. Energy Utilization Systems, Inc., 1980 Survey and Evaluation of Utility Conservation, Load Management, and Solar End-Use Projects; Volume 2: Solar End-Use Projects, EPRI EM-2193, Pittsburg, PA: Energy Utilization Systems, Inc., Jan. 1982.

2. Hirshberg, A., et al., Cost Reduction Opportunities: Residential Solar Systems, Bethesda, MD: Booz-Allen and Hamilton, Jan. 1981.

3. Costa, J. B., "Solar Monitoring by Pacific Gas and Electric Company," Proceedings of the Solar Hot Water Field Test Technical Review Meeting, July 14-15, 1982, Atlanta, GA: Energy Systems Group, DOE/CH/10122-7, Sept. 1982.

4. International Business Machines Corporation, Instrumentation Installation Guidelines, SOLAR/0001-77/15, Huntsville, AL: IBM, Nov. 1977.

5. Argonne National Laboratory, Final Reliability and Materials Design Guidelines for Solar Domestic Hot Water Systems, ANL/SDP-11, Argonne, IL: ANL, Sept. 1981.

6. Wolosewicz, R. M., and J. Vresk, Reliability and Design Guidelines for Combined Solar Space Heating and Domestic Hot Water Systems, ANL/SDP-12, Argonne, IL: Argonne National Laboratory, July 1982.

7. Cole, R. L., et al., Design and Installation Manual for Thermal Energy Storage, ANL-79-15, Argonne, IL: Argonne National Laboratory, Jan. 1980.

8. Ward, D. S., and H. S. Oberoi, Handbook of Experiences in the Design and Installation of Solar Heating and Cooling Systems, SPSP10, Fort Collins, CO: Colorado State University, July 1980.

9. Sparkes, H. R., and K. Raman, "Lessons Learned on Solar System Design Problems from the HUD Residential Demonstration Program," Conference Proceedings: Solar Heating and Cooling Systems Operational Results, SERI/TP-49-063, Golden, CO: Solar Energy Research Institute, 1978.

10. Abrams, D. W., "Installation and Operation Problems Encountered in Residential Solar Systems," Conference Proceedings: Solar Heating and Cooling Systems Operational Results, SERI/TP-49-063, Golden, CO: Solar Energy Research Institute, 1978.

11. Sparkes, H. R., and K. Raman, "Lessons Learned on Solar System Installation Operation and Maintenance Problems from the HUD Solar Residential Demonstration Program," Conference Proceedings: Solar Heating and Cooling Systems Operational Results, SERI/TP-49-063, Golden, CO: Solar Energy Research Institute, 1978.

12. Winn, C. B., and B. W. Parkinson, "Experiences Realized with Air and Liquid Space Heating Systems During the Past Three Years," Conference Proceedings: Solar Heating and Cooling Operational Results, SERI/TP-49-063, Golden, CO: Solar Energy Research Institute, 1978.

13. Moore, D. C., "Lessons Learned from the HUD Solar Demonstration Program," Proceedings of the 1981 AS/ISES Annual Meeting, Vol. 4.1, B. H. Glenn and G. E. Franta, eds., Newark, DE: American Section of the International Solar Energy Society, Inc., 1981.

14. Greenberg, J., S. Berry, P. Chen, P. Cooke, and C. Yancey, Analysis of Reliability and Maintainability of Residential and Commercial Solar Systems Included in the National Solar Heating and Coding Demonstration Program, National Bureau of Standards letter Report to Department of Energy, Sept. 1981. This report also appears as Appendix C, "NBS/HUD Projects Data Analysis" in Cole, M. H., et al., An Assessment of the Field Status of Active Solar Systems, DOE/SF/11485-1, Feb. 1982.

15. Chopra, P. S., and R. M. Wolosewicz, "Freezing Problems in Operational Solar Demonstration Sites," Conference Proceedings: Solar Heating and Cooling Systems Operational Results, SERI/TP-49-063, Golden, CO: Solar Energy Research Institute, 1978.

16. Wolosewicz, R. M., and P. S. Chopra, "Freezing Problems and Other Reliability Concerns in Operational Solar Demonstration Sites," The Final Proceedings of the Second Solar Heating and Cooling Commercial Demonstration Program Contractors Review, Vol. 2, Huntsville, AL: The Johnson Environmental and Energy Center, DOE/CS/4131-1, July 1979.

17. Chopra, P. S., "Solar System Tests Show Improvements in Reliability," Specifying Engineer, Vol. 43, No. 3, Mar. 1980, pp. 53-57.

18. Chopra, P. S., and R. M. Wolosewicz, "Application of Reliability, Maintainability, and Availability Engineering to Solar Heating and Cooling Systems," 1980 Proceedings Annual Reliability and Maintainability Symposium, New York: IEEE Publishing Service, 1980.

19. Chopra, P. S., Reliability and Materials Performance of Solar Heating and Cooling Systems, SOLAR/0906-79/70, Argonne, IL: Argonne National Laboratory, June 1979.

20. Chopra, P. S., "Why Do Solar Systems Fail?" Solar Engineering Magazine, Vol. 5, No. 11, Oct. 1980, pp. 14-21.

21. Kent, T. B., and C. B. Winn, "Performance of Controllers in Solar Heating Systems," Conference Proceedings: Solar Heating and Cooling Systems Operational Results, SERI/TP-245-430, Golden, CO: Solar Energy Research Institute, 1978.

22. Sharp, K., "Reliability Assessment of Active Residential Solar Energy Systems, Phase I," Proceedings of the 1980 AS/ISES Annual Meeting, Vol. 3.2, G. E. Franta and B. H. Glenn, eds., Newark, DE: American Section of the International Solar Energy Society, Inc., 1980.

23. Kendall, P. W., et al., Vitro Laboratories, A Reliability and Maintainability Study of Select Solar Energy System Components in the National Solar Data Network, SERI/TR-254-1848, Golden, CO: Solar Energy Research Institute, March 1983.

24. Meeker, J., and L. Boyd, "The Great, The Good and the Unacceptable," Solar Age, Vol.6, No. 10, Oct. 1981, pp. 29-36.

25. Jones, W. M., "Solar Water Heater Performance Monitoring Program," Workshop on Performance Monitoring of SDHW Systems, Golden, CO: Solar Energy Research Institute, SERI/CP-281-2173, June 1983.

26. Jacobs, R. A., "Operational Status of 134 Solar Water Heaters in the Southeastern United States," Proceedings of the Solar Hot Water Field Test Technical Review Meeting, July 14-15, 1982, DOE/CH/10122-7, Atlanta, GA: Energy Systems Group, Sept. 1982.

27. Smith, R. O., and J. F. Meeker, "One Hundred Solar Water Heaters; Some Lessons Learned About Installation and Performance at New England Electric," Proceedings of the 1978 AS/ISES Annual Meeting, Vol. 2.1, K. W. Boer and G. E. Franta, eds., Newark, DE: American Section of the International Solar Energy Society, Inc., 1981.

28. Albright, S., Solar Domestic Hot Water Project Interim Report, Albuquerque, NM: Public Service Company of New Mexico, Mar. 1981.

29. McKeever, P. S., private communication, Albuquerque, NM: Public Service Company of New Mexico, 5 Apr. 1983.

30. Avril, F. P., "Solar Energy and Electricity are Working Together on Long Island," presented at the Workshop on Performance Monitoring of Solar Domestic Hot Water Systems, Florida Solar Energy Center, 4 Dec. 1980.

31. Hooks, S., private communication, Mineola, NY: Long Island Lighting Company, 25 May 1983.

32. Hooks, S., Long Island Lighting Company Solar Domestic Hot Water Demonstration Program, October, 1978 to December, 1982, Draft, Mineola, NY: Long Island Lighting Company.

33. Long, J., private communication, Knoxville, TN: Tennessee Valley Authority, 2 June 1983.

34. Tennessee Valley Authority, Memphis '1000' Solar Water Heating Demonstration Project, Monitoring Data Analysis Interim Report, October 1981-March 1982, TVA/OP/ECR-83/8, Knoxville, TN: TVA, Nov. 1982.

35. Sawyer, S. W., "The Cost Performance and Reliability Patterns of Solar Heating Systems: An Assessment by 177 Owners," Conference Proceedings: Solar Heating and Cooling Systems Operational Results, SERI/TP-49-063, Golden, CO: Solar Energy Research Institute, 1978.

36. Odegard, D. S., "Early-Life Maintenance Requirements of 124 HUD-Approved SDHW Systems Installed Between 1978 and 1980," Proceedings of the Solar Hot Water Field Test Technical Review Meeting, July 14-15, 1982, DOE/CH/10122-7, Atlanta, GA: Energy Systems Group, Sept. 1982.

37. Argonne National Laboratory, Solar Data Project Plan, ANL/SDP-TM-78-1, Argonne, IL: ANL, Sept. 1978.

38. Freeborne, W., and G. Mara, The Use of Active Solar Heating and DHW Systems in Single Family Homes: Technical Findings and Lessons Learned from the HUD Solar Demonstration Program, Draft, Washington, DC: Department of Housing and Urban Development, Dec. 1982.

39. Schiller, S. R., "Freeze Protection," Solar Age, Vol. 6, No. 8, Aug. 1981, pp. 26-29.

40. Greenberg, J., private communication, Washington, DC: National Bureau of Standards, 19 Sept. 1983.

41. Skoda, L. F., and L. W. Masters, Solar Energy Systems--Survey of Materials Performance, NBSIR 77-1314, Washington, DC: National Bureau of Standards, Oct. 1977.

42. Graham, B. J., "A Survey of Evacuated Solar Collectors," Proceedings of the 1980 AS/ISES Annual Meeting, Vol. 3.2, G. E. Franta and B. H. Glenn, eds., Newark, DE: American Section of the International Solar Energy Society, Inc., 1980.

43. Mather, G. R., "The Sunpak® Evacuated Tube Collector: Field Experiences and Developments," NESEA '77: Better Thermal Utilization; Proceedings of the Second Annual Conference and Exhibition of the New England Solar Energy Association, Brattleboro, VT: New England Solar Energy Association, pp. 355-359, 1977.

44. Yellott, J. E., "Solar Energy Utilization for Heating and Cooling," ASHRAE Handbook and Product Directory 1974 Applications, New York: American Society of Heating, Refrigeration and Air Conditioning Engineers, Inc. 1974.

45. Waksman, D., and A. Dawson, "The Influence of Environmental Exposure on Solar Collectors and Their Materials," Proceedings of the 1980 AS/ISES Annual Meeting, Vol. 3.1, G. E. Franta and B. H. Glenn, eds., Newark, DE: American Section of the International Solar Energy Society, Inc., 1980.

46. Wendel, R. K., and R. E. Dammann, "Results of Long Term Environmental Exposure on Solar Collectors and Their Materials," Proceedings of the 1981 AS/ISES Annual Meeting, Vol. 4.1, B. H. Glenn and G. E. Franta, eds., Newark, DE: American Section of the International Solar Energy Society, Inc., 1981.

47. Yancey, C. W. C., A Summary of Materials Research Activities (1975-1982) Pertaining to Active Solar Heating and Cooling Systems, Draft, Washington, DC: National Bureau of Standards, 1983.

48. Mavec, J. A., Reliability and Maintainability Evaluation of Solar Collector and Manifold Interconnections, Solar/0901-79/70, Argonne, IL: Argonne National Laboratory, Mar. 1979.

49. Baylin, F., Low Temperature Thermal Energy Storage: A State-of-the-Art Survey, SERI/RR-54-164, Golden, CO: Solar Energy Research Institute, July 1979.

50. Clark, E. J., et al., Solar Energy Systems--Standards for Screening Plastic Containment Materials, NBSIR 82-2533, Washington, DC: National Bureau of Standards, June 1982.

51. Goldberg, M. M., "Solar System Performance and Component Reliability After Five years," Conference Proceedings: Solar Heating and Cooling Systems Operational Results, SERI/TP-49-063, Golden, CO: Solar Energy Research Institute, 1978.

52. Versar, Inc., Survey and Evaluation of Available Thermal Insulation Materials for Use on Solar Heating and Cooling Systems, DOE/CS/3563-TI, Springfield, VA: and Butler, PA: Burt, Hill, Kosar, Rittlemann Associates, Mar. 1980.

53. Franklin Research Institute, Installation Guidelines for Solar DHW Systems in One- and Two-Family Dwellings, HUD-PDR-407, Philadelphia, PA: Franklin Research Institute, May 1980.

54. Factors Affecting the Service Life of Phase Change Storage Systems, NBSIR 81-2422, Washington, DC: National Bureau of Standards, Feb. 1982.

55. Eisenbert, D., and C. Wyman, "What's in Store for Phase Change?" Solar Age, May 1980, pp. 12-16.

56. Metz, F. E., and M. J. Orloski, State-of-the-Art Study of Heat Exchangers Used with Solar-Assisted Domestic Hot Water Systems (Potential Contamination of Potable Water Supply), NBSIR 78-1542, Washington, DC: National Bureau of Standards, Oct. 1978.

57. BE&C Engineers, Inc., Final Report of the Management Support Contractor for the Residential Solar Heating Demonstration; Volume IV, Corrosion Problems, Seattle, WA: BE&C Engineers, Inc., June 1983.

58. Avery, J. G., and J. J. Krall, "Control System Corrosion by Monitoring Glycol Fluids," Solar Engineering and Contracting, Vol. 1, No. 3, Mar. 1982, pp. 30-36.

59. Avery, J. G., and J. J. Krall, "Extend System Lifetimes by Reducing Corrosion," Solar Engineering and Contracting, Vol. 1, No. 2, Feb. 1982, pp. 35-39.

60. Avery, J. G., and J. J. Krall, "Sustain Solar System's Efficiency by Protecting Against Corrosion," Solar Engineering and Contracting, Vol. 1, No. 4, Apr. 1982, pp. 22-26.

61. Sullivan, T., "Solar Heat Transfer Fluids," Solar Age, Dec. 1980, pp. 33-36.

62. Youngblood, W. W., et al., Solar Collector Fluid Parameter Study, PB80-125891, Huntsville, AL: Wyle Laboratories, prepared for the National Bureau of Standards, Washington, DC, Oct. 1979.

63. Cheng, C. F. et al., "Corrosion Problems Associated with Solar Fluid and Components," Solar Engineering-1981, edited by R. L. Reid, et al., CONF-810405, 27 Apr.-1 May 1981, pp. 728-738.

64. Foresti, R. J., Jr., Corrosion and Scaling in Solar Heating Systems, SOLAR/0909-81/70, Silver Spring, MD: Vitro Laboratories, Dec. 1981.

65. Avery, J. G., Status Report on the Establishment of a Data Base on Corrosion and Fluids, LA-UR-82-3013, Los Alamos, NM: Los Alamos National Laboratory, Nov. 1982.

66. Corrosivity of Propylene Glycol Solution in Solar Energy Fluid Systems, ANL/EES-TM-131, Woodridge, IL: ECA, Inc., Sept., 1980.

67. Santor, D., "Advantages of Drainback System in Freeze Protection," Solar Engineering, Oct. 1979, pp. 35-36.

68. Kimball, B. A., "How to Get Reliable Freeze Protection for Solar Collectors," Solar Engineering, Mar. 1981, pp. 24-27.

69. Farrington, R. B., Failure Testing of Selected Active Solar Energy System Components, SERI/TR-253-2187, Golden, CO: Solar Energy Research Institute, forthcoming.

70. Waite, E., et al., Reliability and Maintainability Evaluation of Solar Control Systems, SOLAR/0903-79/70, Argonne, IL: Argonne National Laboratory, Mar. 1979.

71. Farrington, R. B. and D. Myers, Evaluation and Laboratory Testing of Solar Domestic Hot Water Control Systems, SERI/TR-254-1805, Golden, CO: Solar Energy Research Institute, Feb. 1983.

72. ESG, Inc., Survey of System Operational Failure Modes From 122 Residential Solar Water Heater Systems Over a Period of Approximately Two Years, ESG-R107-83, Atlanta, GA: ESG, Inc., Jan. 1984.

APPENDIX

STATISTICAL TEST OF SIGNIFICANCE INVOLVING SAMPLE DIFFERENCES

Percent failures (proportions) are expected to follow a binomial distribution. For a large sample size (number of observations, N greater than 30), the binomial distribution can be approximated by a normal distribution. In this case a standardized Z-test can be used to compare the statistical significance of the difference of two percentages at a specified confidence level, say, 95% (level of significance, $\alpha = 0.05$) [1]. Several hypotheses can be formulated, namely:

- H_o--the null hypothesis which holds that the observed difference is due to chance
- H_1--the observed difference is statistically significant.

Deciding between H_o and H_1 involves what is known as a two-tailed normal deviate test. The standardized variable is computed as [2]:

$$Z_o = \frac{P_1 - P_2}{S_{P_1 - P_2}} ,$$

where

$$S_{P_1 - P_2} = \sqrt{pq \frac{N_1 + N_2}{N_1 N_2}} .$$

$S_{P_1 - P_2}$ is the standard error under the null hypothesis with

P_i = observed percentage/100% (proportion)

N_i = number of observations involved in determining P_i

i = 1,2

$$p = \frac{N_1 P_1 + N_2 P_2}{N_1 + N_2} ,$$

$q = 1 - p$.

The observed normal deviate Z_o is thus computed and compared with a critical value Z_c to accept or reject the null hypothesis. For $\alpha = 0.05$, we see that $Z_c = 1.96$. Thus, if $Z_o > Z_c$, the hypothesis that the observed difference in percentages ($P_1 - P_2$) is due to chance is rejected, and the hypothesis that the difference is statistically significant at a 95% confidence level (i.e., there is a 95% probability that the observed percentages are different) is accepted.

However, it should be remembered that this approach is only valid for large numbers of observations (N_1 and N_2 greater than 30). Many of the studies contained in this report dealt with small numbers of systems. In these cases, conclusions regarding relative percentages cannot be statistically supported using this approach, and a small-sampling theory must be applied. In this case, however, an estimate of the standard error associated with each proportion must be known, and this information was not readily available from the data reported in the studies included in this report. In general, the diverse nature of the data reported in the literature precludes any more sophisticated statistical analyses than the normal deviate test, and this test is limited to studies based on a large number of systems.

REFERENCES

1. Thompson, P., private communication, Columbus, OH: Ohio State University, 23 Dec. 1983.

2. Snedecor. G. W., and W. G. Cochran, Statistical Methods, Ames, IA: The Iowa State University Press, 1967, pp. 220-221.

SELECTED DISTRIBUTION LIST

John Avery
Los Alamos National Laboratory
MS K-573
P.O. Box 1663
Los Alamos, NM 87545

Donald Bowden, President
Solar Unlimited, Inc.
No. 37 Traylor Island
Huntsville, AL 35801

Craig Christensen
Solar Energy Research Institute
1617 Cole Boulevard
Golden, CO 80401

Kirk Collier, Ph.D.
Collier Engineering
Rt. 2, Box 240
Cave Creek, AZ 85331

James Collner, Director
Research and Engineering
American Solar King
P.O. Box 7399
Waco, TX 76710

Jonathan Ben Costa
Pacific Gas and Electric Co.
77 Beale Street
San Francisco, CA 94106

Brad Davis, Vice President
Nat'l. Assn. of Solar Contractors
Marc Engineering Corporation
2712 Burgandy Drive
Cinnaminson, NJ 08077

Mr. Robert A. Diehl
Energy Services
Baltimore Gas and Electric
P.O. Box 1475
Baltimore, MD 21203

Robert D. Dikkers
National Bureau of Standards
Technology B-148
Washington, DC 20234

Webb Farber
U.S. Solar Corporation
P.O. Drawer K
Hampton, FL 32044

Robert Farrington
Solar Energy Research Institute
1617 Cole Boulevard
Golden, CO 80401

Lawrence Flowers
Solar Energy Research Institute
1617 Cole Boulevard
Golden, CO 80401

Joe Frissora
Sunmaster Corp.
35 W. William Street
Croning, NY 14830

Ed Gray
JRB Associates
8400 W. Park Drive
McLean, VA 22102

Sally Hooks
Marketing Department
Long Island Lighting Company
250 Old Country Road
Mineola, NY 11501

Peter Jacobs
Novan Energy, Inc.
1630 N. 63rd St.
Boulder, CO 80301

William M. Jones
Energy Systems Group
ESG, Inc.
2231 Perimeter Park, Suite 11
Atlanta, GA 30341

Ronald Judkoff
Solar Energy Research Institute
1617 Cole Boulevard
Golden, CO 80401

Susumu Karaki, Ph.D., Director
Solar Applications Laboratory
Solar House No. 2
Colorado State University
Ft. Collins, CO 80523

Paul W. Kendall
Vitro Laboratories
14000 Georgia Avenue
Silver Spring, MD 20910

William J. Kennish
Vice President
TPI, Inc.
5010 Sunnyside Avenue, Suite 301
Beltsville, MD 20705

Charles Kutscher
Solar Energy Research Institute
1617 Cole Boulevard
Golden, CO 80401

Allan A. Lewandowski
Solar Energy Research Institute
1617 Cole Boulevard
Golden, CO 80401

John Long
Tennessee Valley Authority
400 Commerce Avenue, SW
Knoxville, TN 37902

Pamela S. McKeever
Public Service Co. of N. Mex.
Alvarado Square
Albuquerque, NM 87158

Jack Meeker
8 Gerrity Street
Wilmington, MA 01887

Stan Moore
Los Alamos National Laboratory
MS K-571
P.O. Box 1663
Los Alamos, NM 87545

Lawrence M. Murphy, Ph.D.
Solar Energy Research Institute
1617 Cole Boulevard
Golden, CO 80401

David S. Odegard
Northern Energy Corporation
470 Atlanta Avenue
Boston, MA 02210

Andrew J. Parker
Executive Vice President
Mueller Associates, Inc.
1900 Sulphur Spring Road
Baltimore, MD 21227

Paul J. Pekrul
Rockwell ETEC
P.O. Box 1449
Canoga Park, CA 91304

Gary Purcell
Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, CA 94303

Richard Rittlemann
Burt, Hill, Kosar,
Rittleman Associates
400 Morgan Center
Butler, PA 16001

Sherry Rossi
Vitro Laboratories
14000 Georgia Avenue
Silver Spring, MD 20910

William W. Schertz
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439

Walter Short
Solar Energy Research Institute
1617 Cole Boulevard
Golden, CO 80401

Richard Silberglitt, Ph.D.
DHR, Inc.
6858 Old Dominion Drive
McLean, VA 22101

Robert Spears
Development Project Director
Reynolds Products and Process
Development Laboratory
P.O. Box 27003
Richmond, VA 23261

Bill Stoney
RCA Astro Electronics
P.O. Box 800
Princton, NJ 08540

Burt Swerdling
Project Engineer
Grumman Energy Systems, Inc.
445 Broadhollow Road
Melville, NY 17747

Byron Winn, Ph.D.
Mechanical Engineering Department
Colorado State University
Ft. Collins, CO 80523

Marvin Yarosh
Florida Solar Energy Center
300 State Road 401
Cape Canaveral, FL 32920

Document Control Page	1. SERI Report No. SERI/TR-253-2120	2. NTIS Accession No.	3. Recipient's Accession No.

4. Title and Subtitle A Summary and Assessment of Historical Reliability and Maintainability Data for Active Solar Hot Water and Space Conditioning Systems	5. Publication Date May 1984 6.
7. Author(s) Gary J. Jorgensen	8. Performing Organization Rept. No.
9. Performing Organization Name and Address Solar Energy Research Institute 1617 Cole Boulevard Golden, Colorado 80401	10. Project/Task/Work Unit No. 1598.31 11. Contract (C) or Grant (G) No. (C) (G)
12. Sponsoring Organization Name and Address	13. Type of Report & Period Covered Technical Report 14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)

This report identifies and summarizes 20 R&M studies on active solar energy systems. Most of the data deals with liquid systems for solar domestic hot water applications. The studies showed drainback and recirculation systems to be the most reliable of the liquid systems and antifreeze and oil systems to be moderately reliable. The studies identified storage to be the most reliable subsystem. The problems generally were caused by improper installation or maintenance. Although transport subsystems had many problems, they were not severe. Collector subsystems had a 30%-50% failure rate caused mostly by leaks, damaged glazing seals and gaskets, and freezing. Piping/ducts and controls also have poor reliability and, along with collectors, require further research. Pumps, fans, valves, and dampers are intermediately reliable.

17. Document Analysis

a. Descriptors Control Equipment ; Data ; Demonstration Programs ; Failures ; Fluid Flow ; Heat Storage ; Heat Transfer Fluids ; Performance ; Reliability ; Solar Collectors ; Solar Heating Systems ; Solar Water Heating

b. Identifiers/Open-Ended Terms

c. UC Categories

59

18. Availability Statement National Technical Information Service U.S. Department of Commerce 5285 Port Royal Road Springfield, Virginia 22161	19. No. of Pages 72 20. Price A04

Form No. 0069 (3-25-82)